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# THÈSE POUR OBTENIR LE GRADE DE DOCTEUR DE L'INSTITUT AGRO MONTPELLIER ET DE L'UNIVERSITE DE MONTPELLIER

En Sciences de la Terre et de l'Eau

École doctorale GAIA – Biodiversité, Agriculture, Alimentation, Environnement, Terre, Eau  
Portée par l'Institut Agro Montpellier  
Unité de recherche UMR G-EAU (Gestion de l'Eau, Acteurs et Usages)  
Sun'Agri

**Analysis of the effects of shade combined with water stress on  
the growth and water consumption of maize (*Zea Mays L*) grown  
under AgriVoltaic systems: experimental approach and  
parsimonious modeling in Mediterranean conditions.**

Analyse des effets de l'ombrage combiné à du stress hydrique sur la croissance et la  
consommation en eau du maïs (*Zea Mays L*) cultivé sous systèmes AgriVoltaïques : approche  
expérimentale et de modélisation parcimonieuse en conditions méditerranéennes

**Présentée par Isaac Arturo RAMOS-FUENTES**

**Le 4 octobre 2023**

**Sous la direction de Gilles BELAUD et  
sous l'encadrement de  
Bruno CHEVIRON et Damien FUMEY**

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## ABSTRACT

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AgriVoltaic systems represent a new agricultural tool that allows the production of food and green energy on the same surface while protecting crops from thermal and water stress. In the current context, AgriVoltaic systems could bring certain benefits for field crops, because they occupy large areas and consume large quantities of water, in a context where agriculture is increasingly exposed to droughts due to climate change. "Dynamic" AgriVoltaic systems offer the possibility of optimizing agricultural yield by allowing the level of shade to be modified during the crop's growth cycle. Through this thesis, we studied the combined effects of shading and water stress on the cultivation of maize (*Zea Mays L.*) using different AgriVoltaic systems (fixed and dynamic) under different water regimes. This study was carried out by monitoring and comparing the main agrometeorological variables and the main agronomic indicators (leaf index, phenological stages, total dry biomass, grain yield and soil water status). The principal results show that shade and water stress (combined or separate) have detrimental effects on the growth and yield of maize, as well as a phenological delay and significant reductions in water consumption under shade. Also, we used the Optirrig model, a parsimonious model to simulate the growth and water balance of field crops, to simulate the response of maize under different contrasting conditions of shade and irrigation. This allowed us to identify ways of improvement to consider the effects of shading in AgriVoltaic conditions from simple adaptations, this in the perspective of using this model to optimize agricultural production and water use in these systems from the *in silico* exploration of other scenarios combining shade and irrigation strategies that have not been tested experimentally.

**Key words:** AgriVoltaic systems, Irrigation, Shading, Maize, Crop modeling, Water budget.



## RESUME

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Les systèmes AgriVoltaïques représentent un nouvel outil agricole qui permet de produire des aliments et de l'énergie verte sur la même surface, tout en protégeant les cultures du stress thermique et hydrique. Dans le contexte actuel, les systèmes AgriVoltaïques pourraient apporter certains bénéfices pour les grandes cultures, car elles occupent des larges surfaces et consomment de grandes quantités d'eau, ceci dans un contexte où l'agriculture est de plus en plus exposée à des sécheresses en raison du changement climatique. Les systèmes AgriVoltaïques « dynamiques » offrent la possibilité d'optimiser le rendement agricole en permettant de modifier le niveau d'ombrage au cours du cycle de croissance de la culture. Au travers cette thèse, nous avons étudié les effets combinés de l'ombrage et du stress hydrique sur la culture du maïs (*Zea Mays L.*) à l'aide de différents systèmes AgriVoltaïques (fixes et dynamiques) sous différents régimes hydriques. Cette étude a été réalisée grâce au suivi et à la comparaison des principales variables agrométéorologiques et des principaux indicateurs agronomiques (indice foliaire, stades phénologiques, biomasse sèche totale, rendement du grain et l'état hydrique du sol). Les principaux résultats montrent que l'ombrage et le stress hydrique (combinés ou séparés) ont des effets pénalisants sur la croissance et le rendement du maïs, ainsi qu'un délai phénologique et des réductions importantes sur la consommation en eau sous ombrage. Aussi, nous avons utilisé le modèle Optirrig, un modèle parcimonieux pour simuler la croissance et le bilan hydrique des grandes cultures, pour simuler la réponse du maïs sous différentes conditions contrastées d'ombrage et d'irrigation. Cela nous a permis d'identifier des voies d'amélioration pour prendre en compte les effets d'ombrage en conditions AgriVoltaïques à partir d'adaptations simples, ceci dans la perspective d'utiliser ce modèle pour optimiser la production agricole et l'usage de l'eau dans ces systèmes à partir de l'exploration *in silico* d'autres scénarios combinant des stratégies d'ombrage et d'irrigation qui n'ont pas pu être testées expérimentalement.

**Mots clés :** Systèmes AgriVoltaïques, Irrigation, Ombrage, Maïs, Modélisation de cultures, Bilan hydrique.



## RESUME DE LA THESE

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### OBJECTIF GENERAL

L'objectif principal de cette thèse consiste à étudier les effets de différentes conditions d'ombrage apportées par des systèmes AgriVoltaïques diverses (fixes et dynamiques), couplées à différentes situations de stress hydrique, sur la croissance et le développement du maïs (*Zea mays var. Ixabel*). Le maïs a été choisi comme plante modèle. L'analyse de la réponse du maïs dans des conditions réelles, en présence de combinaisons contrastées d'ombrage et d'irrigation, avait également pour objectif de cibler les processus clés à adapter dans les modèles de cultures génériques pour prendre en compte les effets globaux de l'ombrage sur les principales variables agronomiques de sortie dans ces modèles, ceci afin de faciliter la simulation d'autres conditions et de caractériser les systèmes AgriVoltaïques en termes de rendement et d'utilisation de l'eau.

### OBJECTIFS SPECIFIQUES

- À partir des variables agronomiques obtenues par plusieurs saisons d'expérimentations au champ, caractériser la réponse de la culture de maïs à différentes conditions d'ombrage apportées par des systèmes AgriVoltaïques fixes et dynamiques sous différentes conditions hydriques.
- Décrire et évaluer la différence entre systèmes fixes et dynamiques quant à leurs effets sur la croissance et la teneur en eau du sol afin de déterminer si les différents motifs spatiaux et temporels de l'ombrage ont un impact sur la productivité finale et la consommation en eau et si les systèmes dynamiques représentent un avantage agronomique pour les grandes cultures.
- Identifier les processus clés affectés par l'ombrage dans les systèmes AgriVoltaïques ayant un effet déterminant sur la croissance et l'utilisation de l'eau des cultures, afin de proposer des formalismes parcimonieux en modélisation agronomique permettant d'adapter le modèle Optirrig, pour simuler *in silico* des grandes cultures en contexte AgriVoltaïque.
- Évaluer le modèle Optirrig dans sa capacité à rendre compte des résultats expérimentaux sur la croissance et la consommation en eau du maïs sous conditions d'ombrage et du stress hydrique contrastées, avec la perspective d'utiliser ce modèle à des fins opérationnelles et de gestion ou d'optimisation des stratégies d'irrigation et d'ombrage pour des systèmes AgriVoltaïques en grandes cultures.

### APPROCHE ET METHODOLOGIE

Cette thèse est basée, premièrement sur un cadre expérimental avec le suivi de variables météorologiques et agronomiques sur trois saisons de culture de maïs (jugé représentatif des cultures annuelles) et cultivé sur la plateforme AgriVoltaïque de Lavalette (Montpellier, France). Cette plateforme consiste en quatre dispositifs Agrivoltaïques, dont deux fixes (un

dispositif en pleine densité de panneaux similaire à une station solaire au sol ; un dispositif en semi-densité où la moitié des panneaux a été retirée) et deux dispositifs dynamiques (les deux suivant une stratégie de rotation des panneaux appelée « *solar tracking* » conçue pour optimiser la production d'énergie). Ces différents dispositifs génèrent différents motifs spatio-temporels d'ombrage (et donc du rayonnement arrivant aux cultures). Ces différentes stratégies d'ombrage ont été combinées à différents régimes hydriques (confort hydrique, déficit hydrique et non irrigué). Le pilotage des irrigations a été réalisé à partir des valeurs tensiométriques mesurées sur chaque parcelle irriguée en continu. Pour les parcelles en confort hydrique, les irrigations (apports de 40 mm) ont été appliquées dès lors que le potentiel matriciel du sol était inférieur au seuil de -80 à -100 kPa afin d'éviter l'apparition d'un déficit hydrique au cours de la saison. Pour les parcelles en stress, les irrigations ont été réalisées quand la lecture des valeurs tensiométriques arrivait au moins au seuil de -150 kPa afin d'assurer un stress modéré sans être trop sévère.

Ce volet expérimental a été complété par une approche de modélisation dont l'objectif était d'explorer la capacité du modèle Optirrig, un modèle dit parcimonieux (c.à.d. avec peu de paramètres et des variables d'entrée), à rendre compte des résultats expérimentaux obtenus en conditions réelles. L'approche modélisation a pour objectif de permettre l'expérimentation *in silico* d'autres scénarios qui n'ont pas pu être testés dans les trois saisons expérimentales de cette thèse. Le volet modélisation se limite à l'analyse d'une étude de cas en prenant le modèle Optirrig pour l'adapter des formalismes clé du modèle, avec des modifications simples, afin d'améliorer sa capacité à prendre en compte l'ombrage. Le modèle adapté a été utilisé pour simuler la croissance et le bilan hydrique du maïs sous les dispositifs AgriVoltaïques dynamiques en confort et en stress hydrique.

## PRINCIPAUX RESULTATS

### Axe expérimental

Parmi les différentes variables agrométéorologiques mesurées sous les systèmes AgriVoltaïques (AV), la radiation est la variable plus impactée. Les réductions de la radiation cumulée dans la journée sont, dans les dispositifs AgriVoltaïques Dynamiques (DAV) de l'ordre de 29-38% (variation selon l'année), dans le dispositif fixe en semi-densité (AVhalf) de l'ordre de 30-35% et dans le dispositif fixe en pleine densité (AVfull) de l'ordre de 54-56%. L'analyse des dynamiques *infra journalières* de la radiation mesurée à deux positions de référence dans les systèmes AV (sous-panneaux UP et inter-panneaux IP) a montré une distribution spatiale du rayonnement plus homogène dans les systèmes DAV (mais avec des courbes en opposition de phase) par rapport aux systèmes fixes (AVhalf et AVfull).

Concernant l'impact des systèmes AV sur la température de l'air (qui peut être considérée comme l'une des principales variables agrométéorologiques affectant le développement des cultures), les moyennes journalières n'ont été que légèrement affectées par la présence de panneaux, avec des réductions de température de l'ordre de 0 à 1.5 °C. Cela implique également de légères réductions journalières du temps thermique de l'ordre de 0 à 0.5 degrés jour sous le dispositif DAV (ombrage modéré) et de 0 à 1,2 degrés jours sous le dispositif (ombrage élevé). Cela se traduit dans une réduction saisonnière cumulée de 89 et 110 degrés jours, respectivement. Cependant, lorsque l'on considère les moyens horaires de température, obtenues à partir de valeurs prises toutes les 10 minutes, les différences entre les parcelles AV et la parcelle témoin étaient plus larges, comprises entre -5 et +3 °C. En

d'autres termes, des différences plus importantes n'existent que dans les valeurs de température de l'air infra journalière, avec des effets possibles à court terme sur les processus de croissance des cultures.

Concernant le bilan hydrique, la réduction de la radiation sous les panneaux a conduit à des réductions de l'évapotranspiration de référence proportionnelles aux taux d'ombrage. La dynamique du potentiel matriciel du sol mesuré dans les différentes parcelles a montré que le dessèchement du sol était ralenti dans les modalités ombrées par rapport aux modalités en plein soleil, donnant lieu à une conservation de l'eau du sol et une réduction des besoins d'irrigation de l'ordre de 19 à 35 % par rapport à une culture en plein soleil (en conditions de confort hydrique). Également, nous avons estimé une augmentation de la productivité de l'eau d'irrigation dans les parcelles irriguées sous ombrage, cependant la productivité de l'eau totale (irrigation et précipitation) était inférieure sous ombrage.

Les dynamiques du dessèchement du sol mesurées dans les deux positions IP (*Inter-Pannels*) et UP (*Under-Pannels*) étaient très similaires dans les dispositifs DAV, tandis que les dynamiques étaient fortement écartées dans les dispositifs AV fixes. Ce comportement peut être expliqué par la distribution de la radiation qui diverge dans les différents dispositifs à cause des différents motifs spatio-temporels de l'ombrage qu'ils génèrent. Ce résultat souligne l'avantage d'utiliser des systèmes dynamiques pour obtenir une teneur en eau du sol plus régulière dans la parcelle. Les mesures d'échanges gazeux (transpiration et photosynthèse) réalisées sur des feuilles dans les différentes parcelles ont montré un comportement fortement corrélé aux dynamiques de la radiation, ceci en conditions de confort et du stress hydrique. Cependant, le passage de la lumière à l'ombre, et vice-versa, requiert d'un temps d'environ 10 minutes.

Concernant la croissance et le développement de la culture, il a été observé un retard phénologique, de la levée à la floraison, dans toutes les parcelles ombragées par rapport aux conditions sans ombrage (quel que soit le traitement d'irrigation). Le retard était de 5 à 11 jours, selon le taux d'ombrage. Ce retard était plus important sous stress hydrique par rapport à la situation de confort hydrique. De plus, les parcelles sous irrigation déficitaire ont entraîné une désynchronisation entre la floraison mâle et femelle (ce phénomène est un des meilleurs indicateurs de stress et affecte la pollinisation et le rendement.). Cependant, cette désynchronisation a été observée qu'en conditions de stress hydrique mais pas sous confort hydrique (sous ombrage et en plein soleil), ce qui indique que l'ombrage ne provoque pas cet effet. Dans les parcelles non irriguées (sous ombrage ou pas) le stress hydrique sévère a causé une inhibition de la floraison.

Les mesures de l'indice foliaire (LAI) et l'estimation du *phyllochrone* (qui fait référence à la quantité de temps thermique nécessaire pour l'apparition d'une nouvelle feuille) ont révélé que l'effet de l'ombrage sur la croissance végétative était directement proportionnel au taux d'ombrage. Également, il a été observé une réduction dans le nombre final de feuilles sous ombrage (16 feuilles en moyenne en conditions de plein soleil et 12 sous ombrage, en conditions de confort hydrique). Concernant l'effet du stress hydrique combiné à celui de l'ombrage nous avons observé, sur les parcelles AgriVoltaïques sous irrigation déficitaire, que le stress hydrique a provoqué une réduction plus importante du LAI, suggérant un effet combiné et cumulé de l'ombrage et du stress hydrique. Néanmoins, en conditions de fort stress hydrique (présent dans les parcelles en situation pluviale durant l'année sèche en 2020), la condition hydrique des parcelles ombragées a permis la survie des plantes, pendant que



dans la parcelle en plein soleil, il a été observé une mortalité prématurée des plantes dans la quasi-totalité de la parcelle.

Finalement, concernant la production à la récolte, toutes les parcelles sous ombrage, sous stress hydrique ou sous la combinaison des deux stress ont réduit significativement la biomasse sèche aérienne (TDM) et le rendement sec en grain (GY). Pour les situations en confort hydrique, ces réductions ont été du 19 à 34 % (TDM) et de 5 à 29 % (GY) sous le dispositif DAV, de 18 % (TDM) et 9 % (GY) sous le dispositif AVhalf et de 32 % (TDM) et 30 % (GY) sous le dispositif AVfull (les deux dispositifs fixes ont été conduites en confort hydrique uniquement durant une année). En conditions de stress hydrique ces réductions ont été du 40 à 50 % (TDM) et de 22 à 51 % (GY) sous le dispositif DAV, de 45 à 53 % (TDM) et 34 à 48 % (GY) sous le dispositif AVhalf et de 72 à 80 % (TDM) et de 69 à 83 % (GY) sous le dispositif AVfull (ce dernier en conditions pluviales soumises à un fort stress hydrique).

### Axe modélisation

L'analyse de la structure et des principes du modèle Optirrig a permis d'identifier les principales limitations du modèle pour simuler des cultures en conditions AgriVoltaïques. Ces limitations sont principalement liées à l'approche "1D" et aux équations minimalistes utilisées dans les modules "plante" et "bilan hydrique" du modèle. Le modèle Optirrig prédit avec précision la dynamique et les valeurs maximales du LAI dans les conditions de plein soleil avec des légères surestimations. L'implémentation d'une adaptation simple en utilisant un facteur d'ombrage (le taux de réduction net de radiation sur la parcelle) pour pénaliser la valeur du paramètre LAImax a permis au modèle de simuler correctement la dynamique du LAI sous ombrage en conditions de confort hydrique. Cependant, en conditions de stress hydrique, les prédictions du LAI divergent des dynamiques obtenues par expérimentation. Cette divergence et principalement dû à une forte sensibilité du LAI au facteur de stress hydrique impactant la courbe logistique du LAI dans le modèle, indiquant que le modèle n'est pas performant pour capturer correctement le stress hydrique.

Concernant la simulation de la production de biomasse, Optirrig a surestimé la TDM dans les parcelles en plein soleil et en confort hydrique. Sous ombrage, l'adoption d'une approche dite «Sun-Shade » pour remplacer le formalisme du type « Big-Leaf » dans le modèle a résulté effective pour améliorer les simulations de TDM. L'approche Sun-Shade (SS) proposée consiste à séparer la canopée en deux « grandes feuilles », une ensoleillée et une ombragée, en considérant la fraction de la canopée ombragée par les panneaux dans les systèmes AV. Cette différenciation en deux fractions sert à capturer les différentes réponses de la photosynthèse à la radiation directe et à la radiation diffuse (cette dernière étant la seule radiation capturée sous ombrage). Cette approche a été comparée à deux autres adaptations du modèle, une réduisant la radiation directement à partir des mesures locales sous le dispositif AgriVoltaïque et l'autre pénalisant le RUE, qui est le paramètre clé contrôlant l'efficacité de la transformation de la radiation en biomasse, avec le taux d'ombrage de manière similaire à l'adaptation réalisée pour l'estimation du LAI sous ombrage. Les prédictions de TDM à partir du modèle Optirrig avec l'approche SS ont été plus proches des mesures obtenues en expérimentation par rapport aux autres deux méthodes.

Concernant les variables du bilan hydrique du sol, la boucle hydro-agronomique d'Optirrig a simulé correctement la dynamique de la teneur en eau du sol pour les parcelles en plein soleil ou sous ombrage et en conditions de confort hydrique ou de stress hydrique, ce qui suggère une force du modèle pour simuler le bilan hydrique dans différentes conditions. Les

différentes adaptations implémentées pour affiner la prédiction du bilan hydrique sous ombrage ont donné des résultats similaires. L'adaptation la plus facile à appliquer, et celle de pénaliser l'évapotranspiration de référence à partir du facteur d'ombrage (le même facteur appliqué pour le LAI). Dans cette analyse, l'effet des panneaux sur la redistribution des précipitations n'a pas été inclus et il est recommandé de réaliser des mesures spécifiques pour évaluer l'évapotranspiration réelle, par exemple avec l'utilisation de lysimètres. Également, il est conseillé de réévaluer le calcul du terme de stress hydrique, qui est directement lié à l'ensemble des calculs du modèle et qui semble provoquer des erreurs de prédiction pour le LAI et le bilan hydrique.

## DISCUSSION GENERALE

### Axe expérimental

Le délai phénologique observé dès l'émergence jusqu'à la floraison a été proportionnel à l'intensité de l'ombrage. Sur le délai à l'émergence, la principale hypothèse est que ce délai a été influencé principalement par la température du sol, étant donné que dans notre étude la seule différence entre les parcelles lors du semis était l'ombrage. La température du sol n'a pas été mesurée dans cette étude, mais d'autres travaux précédents sur la même plateforme ont déjà mis en évidence une réduction significative de cette variable sous les panneaux (Marrou et al., 2013a). Une réduction de la température du sol a également été reportée dans différentes études en Agrivoltaïsme (Armstrong et al., 2016 ; Amaducci et al., 2018). Le délai à l'émergence peut être la principale explication pour le délai des stades phénologiques ultérieurs (apparition des feuilles et floraison). Cependant, à partir du calcul du *phyllochrone* (le temps thermique nécessaire pour l'apparition d'une nouvelle feuille), nous avons pu constater que l'ombrage provoque aussi un ralentissement dans la formation des feuilles. Des résultats similaires ont été discutés par Birch et al. (1998a, b) dans des conditions atmosphériques contrôlées et sur le terrain. Cette réponse à l'ombrage était probablement due à la relation étroite entre le rayonnement et la température de l'air. Au fait, il était intéressant d'observer que l'apparition des feuilles montrait une relation linéaire au rayonnement, similaire au temps thermique. Aussi, à partir de nos résultats, nous pouvons affirmer que le facteur l'eau n'influence pas le *phyllochrone*. Ainsi, on peut en déduire que le délai observé pour la floraison était probablement plus lié au développement des stades foliaires, également affectés par l'ombrage. Dans ce sens, Earley et al. (1966) ont également rapporté un retard de la floraison du maïs sous ombrage, mais lorsque l'ombrage était appliqué pendant la croissance végétative (évitant ainsi le retard de l'émergence tel que dans nos expériences). La désynchronisation entre la floraison mâle et femelle sous conditions de déficit hydrique a été également montrée par Nesmith et Ritchie (1992) sur le maïs.

A partir des résultats du suivi de la croissance végétative nous avons pu constater que l'évolution du LAI et l'apparition des feuilles étaient comparables sous le dispositif fixe AVhalf et le dispositif dynamique DAV, les deux ayant un taux d'ombrage similaire autour du 30 %, suggérant que, à l'échelle de la parcelle, la croissance végétative n'a pas été influencée par l'hétérogénéité spatiale de la transmission du rayonnement sur la parcelle, qui est différent entre ces deux dispositifs. Cela est probablement dû au fait que, dans les dispositifs fixes, la surface foliaire des plantes plus grandes (recevant plus de rayonnement) compense la surface foliaire des plantes plus petites (dans les zones plus ombragées). Pour compléter cette analyse, des mesures individuelles de surface foliaire allométriques pourraient être utilisées pour décrire les hétérogénéités de la croissance, en particulier dans les dispositifs fixes

(caractérisées par une majeure hétérogénéité spatiale de la radiation disponible pour les cultures). La réduction des valeurs maximales du LAI sous ombrage est expliquée par l'augmentation du temps thermique nécessaire pour l'apparition des feuilles provoqué par l'ombrage (*phyllochrone* plus élevée) et par la réduction du nombre final de feuilles observée sous ombrage. Cela est en contradiction avec la relation inverse entre la capacité photosynthétique maximale optimale et la fréquence des transitions de faible à forte luminosité signalée par Retkute et al. (2015), qui suggèrent que les effets de l'ombre sur la croissance des feuilles dépendront également des motifs infra journaliers de l'ombrage.

Concernant la production de biomasse, à partir des résultats du LAI, il est naturel d'en déduire que cette réduction de surface foliaire, qui représente la source principale pour capturer la lumière et assimiler du CO<sub>2</sub>, explique les effets négatifs rapportés sur les valeurs finales de masse sèche totale (TDM) et de rendement en grain (GY). Ces résultats sont en accord avec ceux documentés par plusieurs auteurs examinant les réponses du maïs sous ombrage (e.g., Mbewe et Hunter, 1986 ; Yuan et al., 2021 ; Zhang et al., 2006). Ces études aussi montrent que les effets du stress dépendent de l'intensité et de la durée du stress, ainsi que du moment auquel le stress est appliqué durant le cycle de culture. En termes de rendement, il est connu que pour des grandes cultures comme le maïs la période reproductive et la période de remplissage des grains sont les plus sensibles au stress hydrique et au stress thermique (Otegui et Bonhomme, 1998 ; Loomis et Connor, 1992 ; Tollenaar, 1977). Etant donné que l'ombrage était maintenu durant toute la saison dans toutes les parcelles AV de notre étude (avec la même stratégie de rotation des panneaux dans les dispositifs dynamiques), il était évident que l'effet l'ombrage allait causer des fortes réductions de rendement.

En ce qui concerne les effets de l'eau, nous avons pu observer à partir des mesures de l'humidité du sol, que les modalités sous irrigation déficitaire ont subi un stress hydrique pendant les périodes de préfloraison et floraison, modalités où les plus faibles rendements ont été également observés. Pour les modalités de maïs non irriguées (en particulier pendant l'année sèche en 2020), un stress hydrique sévère a fortement affecté la culture, causant le flétrissements permanent de la plupart des plants et une forte réduction du rendement dans la parcelle en plein soleil et une diminution du rendement pour les modalités ombragées, confirmant la sensibilité du maïs aux variations erratiques des précipitations (Campos et al., 2004) mais aussi démontrant l'effet protecteur des panneaux dans tels conditions. Cela semble être en accord avec les résultats rapportés par Amaducci et al. (2018), qui suggèrent des rendements moyens de maïs supérieurs et plus constants sous ombrage par rapport à des parcelles en non ombragées en conditions pluviales (leurs résultats proviennent de simulations effectuées avec des données climatiques sur 37 ans). Nous soulignons aussi l'effet du déficit hydrique dans les parcelles non irriguées sur l'inhibition de la floraison (sous ombrage ou non), ce qui affecte la production de la culture.

Les réductions des besoins en eau dans les parcelles en confort hydrique reportés dans notre étude sur le maïs sont proches de celles rapportées pour d'autres cultures étudiées avec des systèmes AgriVoltaïques similaires (Elamri et al., 2018b ; Juillion et al., 2022). L'augmentation de la productivité de l'eau d'irrigation est probablement liée à la capacité des systèmes AV à (i) réduire la demande climatique (e.g. évapotranspiration de référence) et (ii) ralentir la perte en eau du sol, réduisant ainsi l'évapotranspiration réelle. L'écart observé dans la dynamique du dessèchement du sol sous dispositifs AgriVoltaïques fixes peut être lié à deux facteurs : i) à cause de la distribution du rayonnement et ii) à cause de la redistribution de la pluie par les panneaux. Une des principales limitations de cette étude et le manque d'évaluation du niveau

de stress hydrique appliqué dans les parcelles en irrigation déficitaire. Le stress hydrique n'a pas été appliqué de manière contrôlée et n'a pas été quantitativement estimé (on a juste considéré que le maïs était en stress hydrique, car les irrigations ont lieu autour du seuil de -150 kPa sachant que le limite du confort a été estimé à -80 kPa, pour la texture du sol limono-sableux du site). Dans ce sens, l'utilisation d'un indicateur approprié, comme le *Crop Water Stress Index* (CWSI), peut être utile pour évaluer le niveau de stress. De plus, le CWSI peut contribuer à prévenir le stress hydrique dans les systèmes AgriVoltaïques et peut être utilisé pour la planification de l'irrigation, comme il a été démontré dans plusieurs études (Anda, 2009 ; Fattahi et al., 2018 ; Gu et al., 2021).

Finalement, il est important de noter que les conditions contrastées d'ombrage et d'irrigation étudiées dans notre approche expérimentale représentent uniquement des scénarios qui n'ont pas été conçues pour optimiser le système, mais pour étudier la réponse du maïs dans un large éventail de conditions radiatives et hydriques. Les dispositifs AgriVoltaïques fixes et dynamiques étudiés ici ne sont pas les seules configurations possibles, de nombreuses autres possibilités existent en termes d'orientation des panneaux, d'espacement, de dimensions, de hauteur et de rotation (sous les dispositifs dynamiques). Nos conceptions expérimentales soulèvent des questions quant à la généralisation des résultats, car l'ombrage appliqué pourrait être différent dans d'autres configurations, ce qui pourrait induire différentes réponses des cultures. Cependant, ces résultats expérimentaux représentent un précédent pour des futures expérimentations, mais aussi des connaissances qui pourront être utilisées à des fins de modélisation agronomique. Ainsi, des études supplémentaires *in silico* sont nécessaires pour évaluer d'autres stratégies d'ombrage, en particulier dans les dispositifs AV dynamiques, en adaptant la rotation des panneaux (et le taux d'ombrage) durant les différentes phases phénologiques de la culture, dans le but de minimiser les effets de l'ombrage, mais aussi de réduire le stress hydrique.

### Axe modélisation

A partir de notre analyse, on considère que le modèle Optirrig a bien prédit la croissance et le bilan hydrique sous des conditions de plein soleil, montrant une précision dans la simulation la dynamique de l'indice de surface foliaire (LAI), la production de matière sèche totale à la récolte (TDM) et le bilan hydrique du sol, bien qu'il surestime légèrement le LAI et les valeurs de TDM. Ce n'est pas été le cas pour les parcelles en AgriVoltaïsme, où le modèle Optirrig a surestimé significativement le LAI et n'a pas été capable de reproduire les valeurs de TDM en 2021 (avec une forte sous-estimation). Cette performance du modèle était prévisible, compte tenu des limitations du modèle.

Le premier problème est principalement lié à une décorrélation de la température de l'air et des quantités de rayonnement intercepté par les plantes en contexte AgriVoltaïque, qui ne permet pas de traduire les hypothèses implicites habituellement faites dans les modèles de temps thermiques concernant la croissance et le développement des cultures. Le deuxième problème est associé à l'absence de la prise compte de la variabilité existant à l'échelle de la parcelle des conditions de croissance des cultures en contexte AgriVoltaïque (radiation transmise, teneur en eau du sol, fraction ombragée de la canopée et de la réponse associée de la photosynthèse) qui ne peut pas être explicitement décrite et considérée par Optirrig. Ceci fait que la canopée est traitée comme une grande feuille avec une valeur de LAI unique (bien que dynamique), sans séparer cette « feuille » dans ses portions ensoleillée et ombragée (pour décrire la canopée sous les dispositifs AgriVoltaïques).

Dans la plupart de modèles agronomiques, une bonne prédiction du développement végétative est importante pour l'ensemble du modèle. Dans le cas d'Optirrig, le LAI est la variable centrale de l'algorithme de calcul et donc une prédiction de cette variable est une condition *sine qua non* pour estimer des valeurs fiables d'autres variables dans le schéma de calcul. En particulier, les valeurs de LAI contrôlent à la fois la fraction d'interception du rayonnement (ultérieurement la biomasse) et la transpiration des plantes dans Optirrig. Le succès de l'utilisation du taux d'ombrage pour simuler l'évolution du LAI réside dans le fait qu'en pénalisant le paramètre LAImax, qui est un paramètre important de la courbe logistique et qui décrit de développement végétatif, on limite le potentiel de la culture à atteindre son maximum. Néanmoins cette pénalisation simule bien l'effet que l'ombrage a sur la photosynthèse. En effet, l'ombrage joue juste un rôle qui limite quantitativement le processus de photosynthèse. Dans le cas du maïs, la photosynthèse réagit en parallèle à la radiation reçue par les feuilles (confirmé par les mesures d'échanges gazeux de la feuille). Cela signifie qu'on peut corrélérer directement la réduction nette du rayonnement (ou le taux d'ombrage) à la réduction nette de la photosynthèse (ou la TDM). De plus, la performance de ce facteur de taux d'ombrage, qui est une valeur moyenne qui condense des dynamiques de l'ombrage pendant la journée et la distribution spatiale de l'ombrage, indique que ce n'est pas nécessaire de décrit les effets à court terme de l'ombrage intermittent et l'hétérogénéité spatiale de la radiation pour estimer l'effet global sur la culture de maïs, ce qui représente un fort outil de modélisation parcimonieuse.

Bien que l'adaptation en utilisant le taux d'ombrage résout en partie le problème et permet de simuler la croissance végétative en conditions de confort hydrique, le modèle Optirrig n'a pas pu modéliser correctement la dynamique du LAI pour les conditions de stress hydrique de notre étude (sous ombrage ou pas). Dans le modèle, lorsqu'un stress hydrique, modéré ou fort, est estimé à partir du bilan hydrique (plutôt autour de la valeur maximale du LAI), la courbe de LAI chute de manière drastique (ce qui est loin de la réalité). Cela s'explique par la sensibilité de la courbe de LAI au facteur de stress hydrique ( $S_{W\_LAI}$ ), qui influence directement le terme "logistique de la température" (TL) dans l'équation. Plus la valeur de  $S_{W\_LAI}$  diminue par rapport à 1 (qui est la valeur de non-stress), plus les courbes TL et LAI chutent. Cela signifie que le modèle est capable de capturer le stress s'il est faible et si ce stress ne se produit pas autour du maximum valeur du LAI. Pour améliorer le modèle, il est recommandé de modifier la manière dont le facteur  $S_{W\_LAI}$  est utilisé, par exemple en prenant en compte la valeur de LAI du jour précédent ( $i-1$ ) ou en utilisant un effet additif plutôt que multiplicatif. Il est également à souligner que la difficulté à prédire les effets du stress hydrique élevé sur les modèles de culture n'est pas spécifique à Optirrig, mais se retrouve dans d'autres études utilisant d'autres modèles de culture.

Le "taux d'ombrage" utilisé pour réduire directement l'évapotranspiration de référence permet également la prise en compte des effets de l'ombrage dans le calcul de bilan hydrique des systèmes AgriVoltaïques analysés ici. Cela a une explication similaire à celle du LAI, puisque les deux processus qui déterminent la croissance végétative et utilisation de l'eau (la photosynthèse et l'évapotranspiration, respectivement) sont directement contrôlées par la quantité de rayonnement qui arrive à la parcelle. Cependant, ces modélisations avec Optirrig ne permettent pas de modéliser les hétérogénéités spatiales de la teneur en eau caractéristiques de ces systèmes et donc, cette estimation du bilan hydrique est indicative (pour une utilisation opérationnelle du modèle). Dans notre cas d'étude, nous avons modélisé uniquement les parcelles en AgriVoltaïsme dynamique. Dans ce cas, le bilan hydrique estimé

par le modèle peut être considéré comme représentatif de toute la parcelle, puisque dans nos expérimentations, nous avons démontré que la dynamique de la teneur en eau du sol est globalement similaire dans la parcelle dans ces dispositifs (en raison de l'homogénéité de la radiation sur la parcelle). Cependant, dans des dispositifs fixes, il serait conseillé de réaliser au moins deux modélisations, une pour la portion de la parcelle « sous panneaux » et une autre pour la portion de la parcelle « inter-panneaux ». Également, les hétérogénéités spatiales du sol générées par la redistribution des précipitations du fait de la présence de panneaux n'ont pas été analysées ici, mais ils ont été explorés avec détail sur la même plateforme expérimentale par des travaux antérieurs (Elamri et al., 2018a, b).

Le facteur du taux d'ombrage a été testé pour pénaliser l'efficacité d'utilisation du rayonnement ou RUE, qui est un paramètre qui permet de transformer dans une approche Monteith (Monteith, 1972) le rayonnement intercepté par la plante en biomasse. Cette approche a un résultat similaire à celui basé uniquement sur la réduction du rayonnement à partir des mesures locales en AgriVoltaïsme. Cependant, deux approches ont été efficaces uniquement pour prédire la production de matière sèche totale (TDM) une année sur deux, selon nos données. Dans le cas d'étude, nous avons observé que l'approche « Sun-Shade » a résulté efficace pour prédire la TDM en contexte AgriVoltaïque les deux saisons. Cela est dû au fait que cette approche est appropriée pour décrire les conditions d'ombrage, car il s'agit d'un environnement hétérogène et le fait de séparer la canopée en deux grandes feuilles, une ensoleillée et l'autre ombragée, permet de considérer les différentes réponses de la photosynthèse sous rayonnement direct et sous ombrage (uniquement recevant le rayonnement diffus). Cela indique aussi que l'interception des rayonnements devrait être la première cible de l'adaptation quand on modélise la biomasse en contexte AgriVoltaïque puisqu'elle est le processus clé qui détermine la source d'énergie de la photosynthèse. Ce processus est aussi important pour le bilan hydrique, car l'interception du rayonnement est aussi le « catalyseur » des flux d'eau. Cependant, une des limitations de notre étude, est que la biomasse n'a été mesurée qu'à la récolte et donc nous n'avons pas pu vérifier si le modèle était capable de décrire la dynamique d'accumulation de biomasse tout au long de la saison.

Dans les améliorations envisageables, on pourrait envisager la possibilité de rassembler les effets de l'ombrage et du stress hydrique dans un seul un facteur approprié pour les systèmes AgriVoltaïques. Ce facteur peut être basé sur la conductance stomatique, puisque cette réponse de la plante contrôle à la fois l'assimilation photosynthétique du CO<sub>2</sub> et la transpiration de H<sub>2</sub>O, à travers des échanges gazeux avec l'atmosphère, cela à l'échelle de la feuille, mais aussi à l'échelle de la canopée entière. Notamment, les modèles de conductance stomatique ou les modèles couplés photosynthèse-respiration (basés également sur la conductance stomatique) représentent un moyen d'optimiser l'usage de l'eau et la production de matière sèche, ce qui pourrait être utilisé à des fins opérationnelles à travers de la détermination de bonnes pratiques de pilotage des panneaux couplées à des bonnes pratiques d'irrigations pour les systèmes AgriVoltaïques.

## CONCLUSIONS GENERALES

Cette thèse présente une étude centrée sur la caractérisation de la réponse d'une grande culture de référence (maïs) à un environnement ombragé dans des systèmes AgriVoltaïques sous différentes conditions de stress hydrique. Pour atteindre cet objectif, la thèse a eu deux parties de résultats expérimentaux et d'efforts de modélisation a été réalisée. Elle compare également les systèmes AgriVoltaïques fixes et dynamiques afin d'évaluer les avantages agronomiques potentiels des systèmes dynamiques en termes de réduction des hétérogénéités spatiales de la production agricole et de la teneur en eau du sol dans les systèmes AgriVoltaïques fixes. Dans ce travail, l'efficacité du modèle Optirrig, un modèle parcimonieux, a également été évaluée pour simuler la croissance du maïs et sa consommation d'eau, dans le but d'ouvrir la possibilité d'étendre, dans de futures recherches, l'exploration d'autres scénarios non testés dans cette thèse.

L'objectif agronomique principal était d'analyser comment l'ombrage des systèmes AgriVoltaïques combiné à différents régimes d'irrigation affectait le développement du maïs en conditions expérimentales au champ. Dans l'ensemble, les expériences menées dans cette étude démontrent que, bien que les systèmes AgriVoltaïques puissent influencer les conditions microclimatiques, leur impact sur la température de l'air, l'humidité et le vent est minime. En termes de phénologie, on peut conclure que l'ombre entraîne des retards dans l'émergence des plantes, ce qui affecte ensuite le développement phénologique ultérieur, y compris les stades foliaires et la floraison. De plus, le nombre de feuilles par plante est réduit et le phyllochrone (le temps nécessaire à la formation des feuilles) est plus long sous l'ombre, ce qui contribue également à un retard de la floraison et à une réduction de la surface foliaire. Le stress hydrique exacerbe les effets de l'ombrage sur le retard phénologique et peut causer un échec de la floraison s'il est sévère (comme observé dans les conditions sans irrigation). La relation entre l'apparition des feuilles et le rayonnement était similaire à celle avec le temps thermique, ce qui suggère une forte corrélation entre l'apparition des feuilles et la radiation reçue par les plantes (avec une potentielle utilité pour décrire les hétérogénéités de la croissance des plantes dans les systèmes AgriVoltaïques).

Ensuite, une conclusion générale est que l'ombrage maintenu tout au long de la saison a des effets négatifs significatifs sur la performance de la culture de maïs, notamment une réduction de la surface foliaire et une diminution de la production agricole, pour les conditions analysées ici. En ce qui concerne la croissance des feuilles, l'effet de l'ombrage était proportionnel au taux d'ombrage (le pourcentage de rayonnement réduit par rapport aux conditions de plein soleil) et l'effet combiné avec le stress hydrique est cumulatif. L'effet du stress hydrique n'était pas proportionnel au pourcentage de réduction de l'irrigation par rapport aux conditions d'irrigation complète, car le stress hydrique est un processus plus complexe qui affecte la fonctionnalité de plantes et n'est pas un phénomène continu (comme l'ombrage dans les systèmes AgriVoltaïques). Cela suggère que le stress hydrique doit être mieux caractérisé et quantifié dans de futures recherches. Les effets de l'ombre et du déficit hydrique sur la croissance des feuilles expliquent la réduction de la production agricole (biomasse et rendement en grain). Cependant, la réduction du rendement était inférieure à celle de la biomasse, probablement en raison de régulations photosynthétiques internes qui doivent être explorées plus en détail.

En ce qui concerne l'utilisation de l'eau, on peut conclure que les systèmes AgriVoltaïques présentent des effets positifs, réduisant les besoins en irrigation et améliorant la productivité

de l'eau d'irrigation dans les cultures de maïs, tout en mettant en évidence les avantages potentiels des structures dynamiques pour réduire les hétérogénéités de l'eau du sol. De plus, la préservation de l'humidité du sol dans les parcelles ombragées peut constituer un tampon contre le stress hydrique et améliorer les chances de survie des cultures dans les conditions pluviales et sèches, en offrant un environnement plus favorable à la croissance des cultures par rapport aux conditions non ombragées.

Un autre objectif initial était de déterminer si les motifs d'ombrage spatiaux et temporels avaient une influence sur la productivité finale et la consommation d'eau du sol. L'étude a révélé que les différents motifs d'ombrage dans les conditions AgriVoltaïques fixes ou dynamiques n'avaient pas d'impact significatif sur la dynamique de croissance des feuilles. En termes d'utilisation de l'eau, les systèmes dynamiques permettent de réduire les hétérogénéités de l'eau du sol par rapport aux systèmes fixes. Cependant, en termes d'irrigation, nos résultats ont montré que la même stratégie d'irrigation sur les deux systèmes conduisait à des rendements similaires, ce qui suggère que dans les systèmes fixes, les hétérogénéités de la teneur en eau du sol sont compensées par les hétérogénéités des plantes individuelles (la production dans les plantes plus vigoureuses compensant les plantes moins vigoureuses). Les résultats indiquent que les systèmes AgriVoltaïques fixes et dynamiques peuvent être également efficaces pour soutenir la croissance des cultures de plein champ et maintenir la teneur en eau du sol. Cela implique que la décision de choisir entre des systèmes fixes et dynamiques ne doit pas nécessairement être basée sur l'impact agronomique, qui est similaire et dépend à grosso modo du taux d'ombrage nette. D'autres facteurs tels que les besoins de contrôle des panneaux pour optimiser le système et augmenter l'homogénéité de la production avec des cultures spécifiques, les objectives de production d'énergie ou les aspects financières et sociétales peuvent jouer un rôle plus important dans la détermination du système préféré.

Enfin, nous ne pouvons pas conclure que la réduction des pertes de rendement du maïs dans des conditions d'ombre est systématique, car l'ombre a été appliquée pendant tout le cycle (sans tenir compte de la tolérance de la culture ni de sa sensibilité phénologique) et donc des recherches supplémentaires seraient nécessaires pour optimiser ces systèmes, en se concentrant notamment sur les stratégies d'ombrage plus adaptées au maïs. Les résultats expérimentaux encouragent de futures recherches pour explorer les interactions entre l'ombre, le déficit hydrique et les réponses des cultures à différentes étapes de développement et dans des conditions de stress variables, et soulignent les limites des modèles de culture existants pour prédire efficacement la production de rendement des cultures.

En ce qui concerne la modélisation, l'objectif central de ce travail était d'identifier les processus clé affectés par l'ombre et d'améliorer et d'évaluer la capacité d'un modèle simple et parcimonieux à simuler avec précision les effets de l'ombre en simulant la croissance du maïs et le bilan hydrique dans les systèmes AgriVoltaïques (dynamiques). Pour cela, nous avons employé le modèle Optirrig pour l'adapter avec des formalismes simples basés sur les conclusions concernant les réponses du maïs à l'ombrage obtenues par expérimentation et en intégrant les connaissances acquises dans des modèles agronomiques génériques, tout en se concentrant sur une culture de référence telle que le maïs. À partir de l'étude de cas présentée ici avec Optirrig, nous pouvons conclure que les formalismes sursimplifiés intégrés dans le modèle pour décrire le rayonnement intercepté, la croissance des feuilles et la photosynthèse ne sont pas adéquates pour prendre en compte l'effet de l'ombre dans les systèmes



AgriVoltaïques et nécessitent des adaptations spécifiques. La variable ciblée principale pour décrire avec précision l'impact des changements environnementaux sur le développement des plantes devrait être l'interception du rayonnement. Une estimation adéquate du rayonnement intercepté, en tenant compte de la fraction ombragée de la parcelle dans les systèmes AgriVoltaïques, devrait être la première cible des adaptations. L'approche dite *sun-shade* qui consiste à séparer la canopée en deux grandes feuilles, une ombragée et une ensoleillée, et l'utilisation d'un facteur de réduction basé sur le taux d'ombrage des systèmes AgriVoltaïques, ont donné de bonnes prédictions de la croissance du maïs, du rendement et du bilan hydrique avec Optirrig.

À partir de cela, nous pouvons conclure que l'approche *sun-shade*, est efficace pour améliorer la prédiction de la production de biomasse par Optirrig. L'adaptation simple proposée utilisant le taux d'ombrage pour affecter les paramètres clé a également montré son efficacité dans l'amélioration des simulations avec Optirrig, mais le manque de soutien écophysiological et son applicabilité dans différents contextes ou avec différents taux d'ombrage et configurations de panneaux restent incertains. En termes de bilan hydrique, le modèle Optirrig semble être robuste pour prédire la dynamique hydrique du sol en conditions d'ombrage et de stress hydrique, ce qui signifie qu'uniquement une estimation correcte de l'évapotranspiration de référence réduite par l'ombre est nécessaire pour corriger les simulations de bilan hydrique.

Le modèle Optirrig a démontré sa capacité à rendre compte des résultats expérimentaux obtenus dans cette thèse, ce qui nous permet de conclure que ce modèle (avec certaines adaptations spécifiques) permet de simuler correctement la croissance du maïs en conditions AgriVoltaïques sous stress hydrique légère ou modéré et peut être utilisé à des fins opérationnelles pour monitorer ou gérer la culture et pour simuler d'autres *scenarii in silico* afin d'explorer des stratégies d'ombrage et d'irrigation à des fins d'optimisation agronomique, environnementale ou financière. Cependant, il est important de garder en tête que le modèle Optirrig doit être utilisé avec précaution, car il reste un modèle simplifié et nécessite une validation supplémentaire dans des conditions expérimentales plus diverses.

En conclusion, cette thèse a contribué à une meilleure compréhension de l'impact de l'ombre et du régime d'eau sur le développement du maïs dans les systèmes AgriVoltaïques. Les résultats expérimentaux ont montré que l'ombre a des effets significatifs sur la phénologie, la croissance des feuilles et la productivité du maïs, tandis que le stress hydrique exacerbe ces effets négatifs. Également, nous avons confirmé que les systèmes AgriVoltaïques peuvent réduire les besoins en irrigation et améliorer l'utilisation de l'eau pour la culture de maïs. En ce qui concerne la modélisation, le modèle Optirrig a été amélioré pour prendre en compte l'effet de l'ombre, mais des adaptations supplémentaires sont nécessaires pour mieux prédire la réponse du maïs dans les systèmes AgriVoltaïques. Les résultats présentés ici fournissent des informations précieuses pour la conception et la gestion des systèmes AgriVoltaïques et ouvrent la voie à de futures recherches et expérimentations *in silico*. La validation du modèle Optirrig permettra, à travers d'une approche parcimonieuse, l'optimisation de ces systèmes pour une production agricole durable. Particulièrement, l'étude du pilotage des panneaux photovoltaïques pour coupler et optimiser des stratégies d'ombrage et d'irrigation spécifiques au maïs (ou d'autres grandes cultures) semble intéressant pour la suite de recherches. Cette optimisation multicritère devra prendre en compte des variables objectives comme la production agricole, l'usage de l'eau, la production d'énergie et le revenu économique sous les systèmes AgriVoltaïques.

## PREAMBULE

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This thesis is part of the Sun'Agri 3 research program (<https://bibliothèque.ademe.fr/recherche-et-innovation/1049-sun-agri-3.html>), resulting from the collaboration between Sun'Agri, a branch of Sun'R groupe (producer of photovoltaic energy), and the UMR G-EAU (INRAE). This third phase of the Sun'Agri program focuses on the analysis of the needs of plants throughout their growth cycle in AgriVoltaic conditions, combining them with meteorological and farm data. Thus, the main objective of this program is to understand the crop responses to address agricultural production objectives, with a “crop first” vision. Sun'Agri 3 follows the Sun'Agri 2 program, which included the thesis works of (i) Valle (2017), focused on modeling and optimization of the photovoltaic panels' orientation for biomass production of lettuce crop (*Lactuca sativa* L) under dynamic AgriVoltaic systems and (ii) Elamri (2018), focused on the study and modeling of water balance of lettuce under AgriVoltaic systems. Both works were developed by experimentations carried out in the experimental platform of Lavalette (Montpellier, France), including fixed and dynamic AgriVoltaic systems. The adjective “dynamic” was introduced to emphasize the importance of being able to modulate the shade, thanks to adjustable panels, depending on radiative needs of crops.



## OBJECTIVES

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### GENERAL OBJECTIVE

The main objective of this thesis is to study the effects of different shade conditions provided by diverse AgriVoltaic systems (fixed and dynamic), in conjunction with different water stress conditions, on the growth and development of maize (*Zea mays var. Ixabel*, crop and variety selected to represent field crops). The analysis of the response of maize under real conditions, in the presence of contrasting combinations of shade and irrigation, also has the main objective of targeting the key processes to be adapted in the generic crop models to take into account the global effects of shading on the main agronomic output variables in these models, in order to facilitate the simulation of other conditions and to optimize AgriVoltaic systems in terms of yield and water use.

### SPECIFIC OBJECTIVES

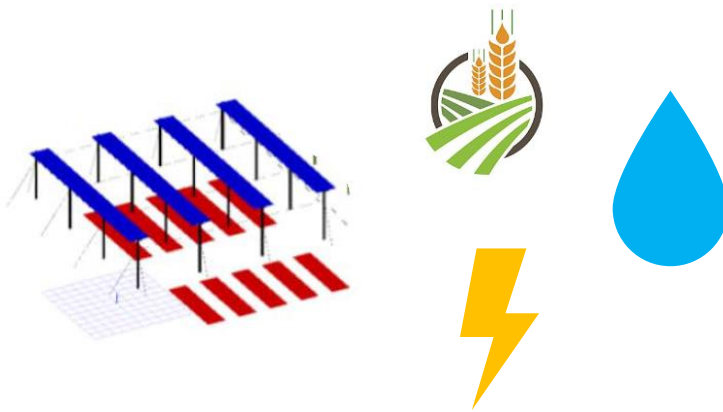
- Based on agronomic variables obtained by field experiments, characterize the response of the corn crop to different shade conditions provided by fixed and dynamic AgriVoltaic systems under distinct water conditions.
- Describe and evaluate the difference between fixed and dynamic systems in terms of their effects on growth and soil water content to determine if the different spatial and temporal patterns of shading have an impact on the final productivity and the consumption of water from soil and if dynamic systems represent an agronomic advantage for field crops.
- Identify the key processes affected by shade in AgriVoltaic systems having a determining effect on the growth and water use of crops in order to propose parsimonious formalisms in agronomic modeling permitting the adaptation of the Optirrig model, the simplest possible, to simulate in silico field crops in an AgriVoltaic context.
- Evaluate the ability of the Optirrig model to simulate the experimental results on the growth and water consumption of maize under contrasting shade and water stress conditions, with the perspective of using this model for operational and management purposes or for optimization of irrigation and shade strategies for AgriVoltaic systems in field crops.



# CHAPTER 1

## BACKGROUND

*“As often happens in science, discoveries are made in the pursuit of an elusive (and sometimes nonexistent) goal.”—  
Stephen Hawking*





## CHAPTER 1 –BACKGROUND

### 1.1 WATER-ENERGY-LAND-FOOD NEXUS: THE ROLE OF AGRICULTURE UNDER THE CLIMATE CHANGE CONTEXT

Global development is currently conditioned by the growth of the world's population (which is projected to be almost 10 billion by the midcentury), causing a general increase in food, water, and energy demands. Coupled with accelerated climate change and land degradation, the risk of a dramatic shortage of natural resources is evident (Reich, 2001; de Amorim et al., 2018). In this context, optimizing the synergies between the interconnected Water, Energy, Land, and Food contributors to human well-being (**the WELF nexus**) is crucial to achieving sustainable development without putting at risk the capacity of the planet base. Among the several human activities, **agriculture** is probably one of the most concerned by the WELF nexus (see Figure 1.1): agriculture production is not only the main supply of food, some crops have become largely used to generate biofuels, also acting as an important energy producer in some regions. Indeed, to satisfy the food demand for the fast-growing population globally, crop production is projected to increase by about 60% (Muhie, 2022).

On the other hand, agriculture is also the main **freshwater user** (Forouzani and Karami, 2011) and occupies large land areas worldwide, sometimes invading vital world ecosystems like forests (Searchinger et al., 2019). Also, modern agriculture is based on high energy consuming systems, producing global greenhouse gas emissions), and to top it off, agriculture is a major **polluter of water** (78% of the global ocean and freshwater eutrophication is caused by agriculture), according to Poore and Nemecek (2018).

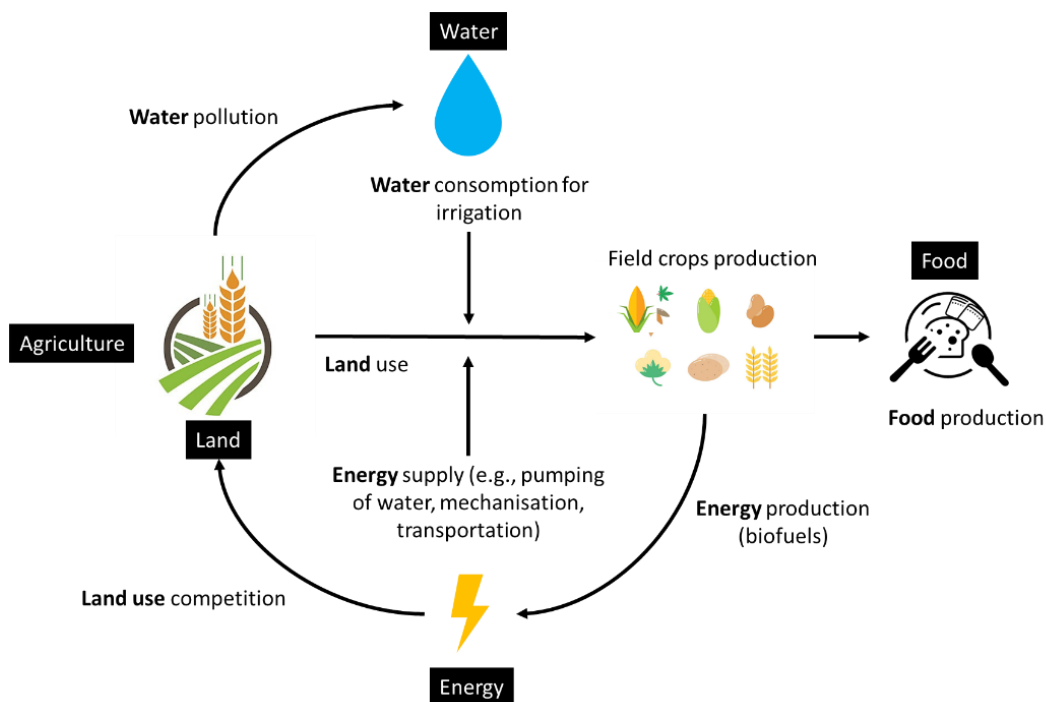


Figure 1.1. Water-Energy-Land-Food Nexus in Agriculture.



Agriculture is reliant on the called “**field crops**” or “major crops” (crops grown on a large scale), including cereals, millet, and oil seeds. The six most widely grown field crops in the world are wheat, rice, maize, soybeans, barley, and sorghum (Lobell and Field, 2007), and their production is essential to supply the existing and constant growing needs (human consumption, livestock feeding, and food chains). In particular, **maize** is one of the most important crops worldwide, because (i) is one of the most preferred crops by farmers due to its high productivity (Steduto et al., 2012); (ii) is essential for **food security** in several **developing countries** (almost 70% of the total maize harvested for human consumption is produced in low and lower-middle-income countries, FAOSTAT, 2022), (iii) is a very important crop for **industry** providing several **raw materials** (Hu et al., 2003) and (iv) is a crop **adapted** to a wide range of **agro-climatic conditions** (grown from below sea level to altitudes higher than 3000 m and in areas with 250 mm to more than 5000 mm of rainfall per year). In consequence, maize is intensely cultivated worldwide, with an average harvested area of 157 Mha in approximately 160 countries (around 35% of the global grain production), occupying the third position of the most important crops, only after wheat and rice.

Nowadays, access to new agricultural areas will be more difficult in the context of “**land scarcity**” caused by land competition (Smith et al., 2010) and other land-reducing factors, such as soil erosion and urbanization (Foley et al., 2011; Khaledian et al., 2017). Despite their economic and societal importance, field crops also have a considerable impact on Earth’s resources: high-yielding agricultural systems are often characterized by high rates of fossil fuel energy consumption, excessive nutrient use, soil degradation, and water pollution (Scanlon et al., 2007).

**Crop yield**, which is the harvested crop production per unit of harvested economically valuable crop products (usually measured in tons per hectare), depends basically on the agro-climatic conditions and the available resources (i.e. energy, water, land, nutrients). According to several authors, agriculture is one of the leading human activities that climate change will strongly impact, especially in poor regions (e.g., Magadza, 2000). Indeed, one of the main factors directly (currently) influencing year-to-year crop yields is **climate variability**, even in high-yield and high-technology agricultural areas. Depending on the latitude and the existing irrigation infrastructure, climate variability is dramatically increased by climate change, which is projected to impact crop production (Kukul and Irmak, 2018; Thornton et al., 2014). In some areas, crop yields will increase because of increased annual **rainfall** (particularly during the cropping season). In other areas, crop yields will decrease, impacted by the more recurrent **agricultural droughts** (a concept more developed in the next section).

According to recent studies (e.g., Noto et al., 2022) it is projected a general increase in both the mean and extreme values of air temperatures, may lead to changes in soil evaporation and plant transpiration. Regional and global climate models predict future soil moisture variability: on average, 15%-29% of the global land area will experience significant soil water depletion by the end of the 21st century (Joo et al., 2020). This projected situation, coupled with the potential impact of climate change on streamflows (e.g., Gaur et al., 2020), will undoubtedly affect crop productivity in the cases where the soil storage capacity will be unable to attenuate the **reduced water availability** (Granados et al., 2021). Moreover, the accompanying decrease in soil moisture increases the risk of extremely hot days and heat waves (Gu et al., 2019; Merrifield et al., 2019) since soil moisture drying can heat the land surface and near-surface air by increasing the portion of sensible heat in the surface energy

budget (Seneviratne et al., 2010), which is consistent with the reduction of evapotranspiration and latent heat release.

Particularly on field crops, the impacts on crops such as maize, wheat, and rice have been studied by several researchers (e.g., Wang et al., 2018). For wheat, maize, and barley, there is a negative response of global yields to increased temperatures (Lobell and Field, 2007). It has been reported that the average yield of four major field crops, namely, maize (*Zea mays*), wheat (*Triticum aestivum*), rice (*Oryza sativa*), and soybean (*Glycine max*), is predicted to decline by 7.4, 6.4, 3.2, and 3.1%, respectively, with every 1°C increase in the mean global temperature (Zhao et al., 2017). Interestingly, the greatest yield losses caused by the high-temperature climate were found in the C4 crop maize but not in C3 crops. This finding was inconsistent with the earlier results that C4 crops always showed higher temperature and radiation tolerance than C3 crops.

Also, an indirect effect of increasing air temperatures is the change in the timing of spring events (e.g., Schwartz and Reiter, 2000) and the prolongation of the growing seasons (e.g., the growing season extended in Europe, according to Menzel and Fabian, 1999). This involves **alterations in the timing and duration of the phenological phases** (i.e., the sequence of the development stages) of field crops, which could be of great economic importance because they could have direct **impacts on yield formation** processes and so on the final crop yield (Chmielewski et al., 2004). The extension of the growing season will more positively affect crop farming in the mid and high latitudes since a longer growing season will improve the scope for cultivars selection, catch cropping, and crop rotation. Shorter developmental periods for field crops could negatively affect the formation of the individual yield components, as for cereals, the crop density, the kernel number per ear, and the kernel weight.

Focusing on water resources (the main terrestrial input for agriculture productivity), there exists an interplay to find in order to ensure the welfare of current and future generations, involving (i) the reduction of agriculture's ecological and climate footprint, especially by **sustainable water use** (Velasco-Muñoz et al., 2018) and (ii) the increase of **crop productivity**, primarily by increasing yield per unit of water (Vos and Bellù, 2019). Both targets are linked by the concepts of **water use efficiency (WUE)** and **water productivity (WP)**, developed more extensively in **Box-a**.

However, both water use and crop productivity in agriculture are strongly affected by **extreme climatic conditions**, like heat waves, storms, drought, salinity, and flooding (McKeivith, 2004; Sillmann and Roeckner, 2008), which are increased by climate change, especially in developing countries. Consequently, innovations and new technologies for saving water-limited resources will be crucial. The following section explores the issues related to water scarcity and its effects on agriculture, as well as the role of irrigation optimization in preserving water and increasing crop yields.

## 1.2 WATER SCARCITY: A WORLD WITH GROWING WATER DEMANDS AND MORE RECURRENT EXTREME EVENTS IMPACTING AGRICULTURE

Globally, climate models predict decreases of renewable surface water and groundwater resources in some regions and increases in others (Haddeland et al., 2011; Hagemann, 2012): **water resources** are projected to decrease significantly in many mid-latitude and dry subtropical regions, being semiarid and arid areas particularly exposed; and to increase at high latitudes and in many humid mid-latitude regions. The increase of **water withdrawals** from several water-dependent ecosystems and water users (livestock, human consumption, and industrial needs), in addition to the impacts of climate change on water resources, has led to a dramatic reduction of terrestrial water storage – the water held in soil, snow, and ice –, increasing competition between water users and creating more and more recurrent territorial and local **water tensions** around the world.

**Water scarcity** is a term used to describe the situation where there is a shortage or inadequate availability of freshwater resources to meet the demands of a particular region or population. It occurs when there is an insufficient supply of water to satisfy the demands of one or some water users (environment, agriculture, industries, and individuals) coexisting in that area supplied by the same headwater. Thus, water scarcity is a general term combining a deficiency of volumetric availability of water, water quality degradation, and limited water accessibility. No continent on Earth has been untouched by water scarcity, and an increasing number of regions are reaching the limit to provide water services sustainably, especially in arid regions.

Water can be scarce for many reasons, the principal being the occurrence of **droughts** (see Figure 1.2). Drought is a normal, recurrent climatic feature that reflects the shortage of water due to short- or long-term rainfall deficits. According to regional observations, **extreme rainfall events** and **meteorological droughts** (low rainfall) have intensely increased since the mid-20th century (Arndt et al., 2010). Notably, droughts have increased in extent and frequency (Sheffield and Wood, 2008). Recent global projections predict that droughts will become longer or more frequent (or both) in certain regions (Vicente-Serrano et al., 2022; Yin et al., 2022). Droughts are projected to intensify in southern Europe, the Mediterranean region, central Europe, central and southern North America, Central America, northeast Brazil, and southern Africa. Depending on their severity, duration, and spatial extent, droughts may lead to low soil moisture content, decreasing groundwater levels, saltwater intrusion, deteriorating water quality, and reduced river discharges.

However, not only droughts (that is not a human-controlled event) may produce water tensions. Punctual or Water availability may be limited by other non-climatic events imposed by authorities due to competition with other uses. Water scarcity may also be caused by an **unbalance of water resources** (the demand for water exceeding supply), caused by inefficient water management, or increased water quality degradation, also called anthropological “**water shortage**.” A major consequence of poor anthropological water management causing water shortage worldwide is the **rapid depletion of the world’s major aquifers**. Water shortages are an increasing problem on every continent, with poorer communities most badly affected by the lack of well-developed water systems. Both climatic drought and anthropological water shortage frequently cause water scarcity. Some areas are in a perpetual drought, whereas others may occasionally deal with short droughts or water shortages.

Among all the water users, irrigated agriculture will probably be the most affected by water scarcity and climate change since it is highly dependent on meteorological conditions and is by far the largest water user: agriculture accounts for almost 70 percent of all water withdrawals for human activities, up to 95 percent in some countries (Schlenker et al., 2007). Depending on the region and water storage capacity, agriculture is yet impacted by water scarcity when the crop water needs are the largest (generally during the dry season with reduced flow rates of rivers) and exceed the local water availability. According to a new study, the situation will worsen: globally, **agricultural water scarcity** is expected to increase in more than 80% of the world's croplands by 2050 (Liu et al., 2022). **Rainfed agriculture** is particularly vulnerable to increasing precipitation variability, which may increase the yield variability and the differences in yield between rainfed and irrigated systems (e.g., Finger et al., 2011). Concerning irrigated areas, it is predicted that about 40% will face severe water scarcity by 2040 (NIC, 2021). This, in addition to the predicted increase in irrigation **water demand of crops** in both irrigated and rainfed systems (Goodarzi et al., 2019; Le Page et al., 2021; Webber et al., 2016), will put in risk the maintenance of global crop productivity.

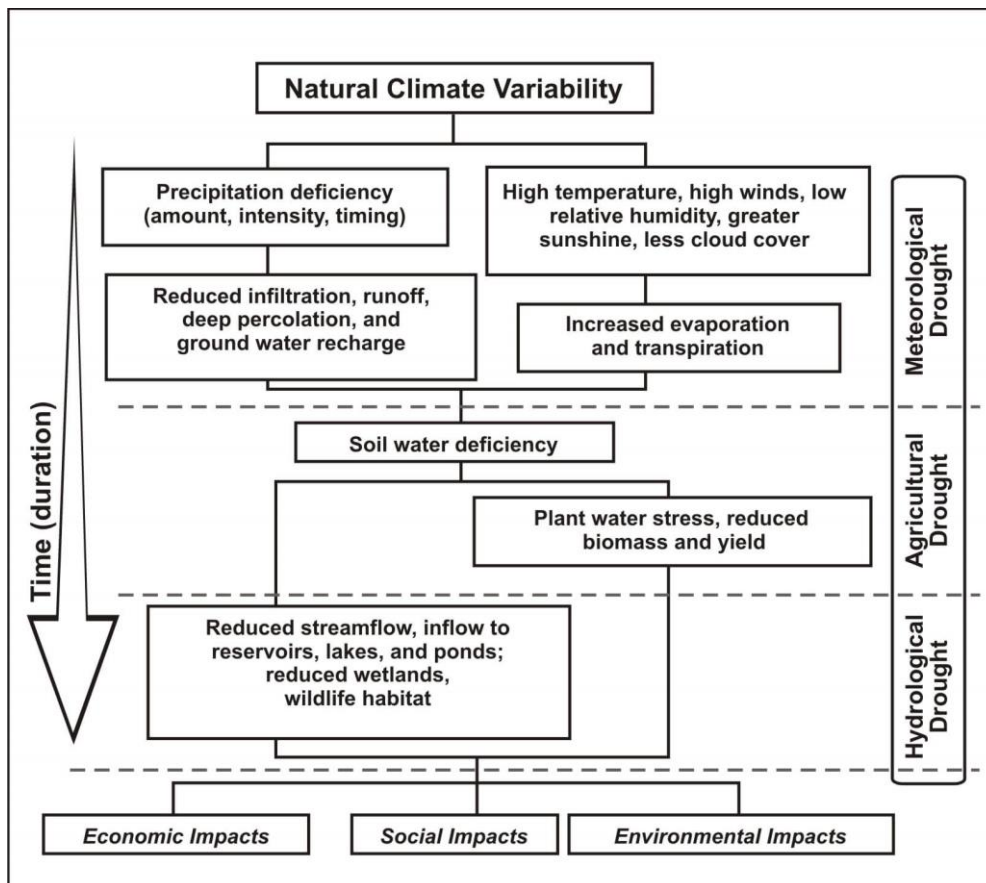


Figure 1.2. The sequence of drought occurrence and impacts for commonly accepted drought types. All droughts originate from a deficiency of precipitation or meteorological drought but other types of droughts and impacts cascade from this deficiency (Source: NDMC).

In crop production, **agricultural droughts** are the most relevant. Agricultural droughts are associated with low moisture in the soil for growing crops, linking various characteristics of meteorological (or hydrological) drought to agricultural impacts. The location, extent, and severity of water scarcity for agricultural production will depend on reduced water availability. According to Mannocchi et al. (2004), an agricultural drought is considered to have

set in when the soil moisture availability to plants has dropped to such a level that it adversely affects the crop yield and hence agricultural profitability. Despite the slight increase in precipitation in wetter regions, globally, the land-atmosphere projections under various warming scenarios indicate that soil moisture will decrease in many regions because of the warmer climate (Berg et al., 2017; Fu and Feng, 2014; Lin et al., 2015), associated with the projected **increase of evapotranspiration rates** (Kingston et al., 2009; Miralles et al., 2011). Regionally, increases in evapotranspiration rates are projected in southern Europe, Central America, southern Africa, and Siberia (Seneviratne et al., 2010).

Nowadays, **crop water stress** is the main factor limiting the productivity of field crops (e.g., maize production; Wang et al., 2014), since numerous production areas worldwide are primarily located in arid and semiarid areas. Indeed, many strategies are implemented to face water scarcity, usually by improving water productivity. In wetter regions, it may be reached using **irrigation systems** followed by optimal water **irrigation management** regarding both timing and quantity of water applied. In dryer conditions with more intense seasonal droughts, water scarcity may be tempered, in addition to correct irrigation management, by other strategies such as reducing evapotranspiration demands and soil water conservation strategies—the following section addresses this topic more in detail.

### 1.3 IRRIGATION: A CRUCIAL STRATEGY TO MANAGE WATER STRESS IN AGRICULTURE

Integrated water management in irrigated agricultural areas is considered one of the main levers to maintain crop productivity in response to climate change and population growth (Carruthers et al., 1997; Darko et al., 2016). Irrigated crops are estimated to sustain 40% of the global food production using just 20% of the total cultivated land, typically doubling the yield compared to rain-fed conditions (Abdullah, 2006; Puy et al., 2021). However, **global irrigated land** grew sixfold from 0.5 million km<sup>2</sup> to 3.0 million km<sup>2</sup> in the last century (Freydank and Siebert, 2008), to reach nowadays (2020) some 4.2 million km<sup>2</sup> (FAOSTAT, 2020). For the coming decades, the irrigated area is not expected to expand dramatically due to limited land and (available) water (Faurès et al., 2002; Turrall et al., 2011). In some regions, expanding irrigated areas or increasing irrigation efficiency may overcome climate change impacts on agricultural water demand and use (McDonald and Girvetz, 2013). However, a global modeling study shows that unmitigated climate change may counteract such efforts (Rost et al., 2009). However, this will also be limited by the **lack of irrigation infrastructure**, mainly in developing countries that already use a high proportion of their water resources and limiting the potential for expanding irrigated areas. Moreover, future irrigation needs will probably accelerate the depletion and pollution of rivers and aquifers if the resource is not well managed (Scanlon et al., 2007). In this context, **adaptation to climate change** in agricultural water use can contribute to preserving global and regional water resources.

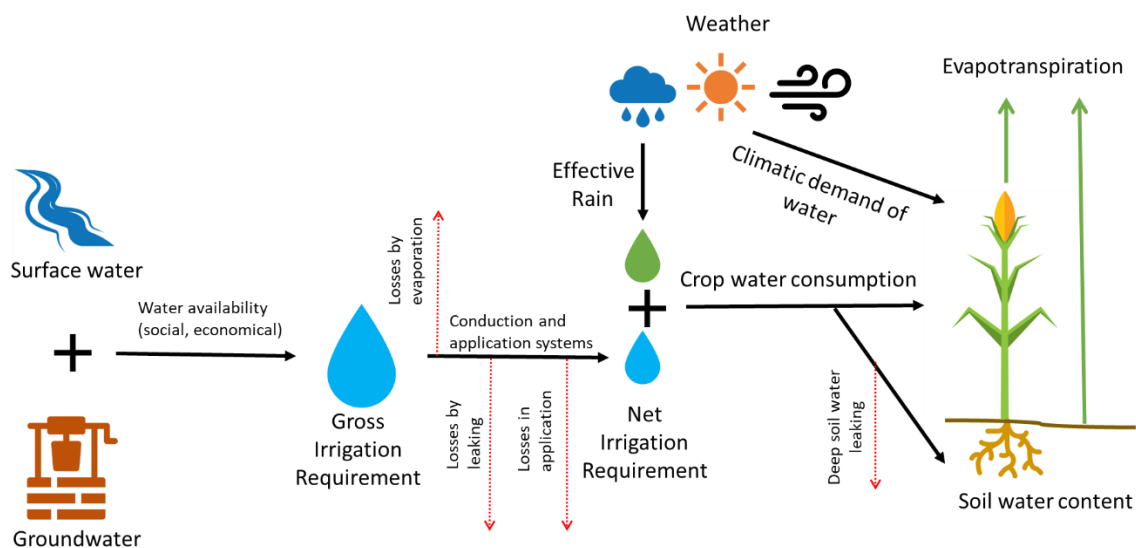


Figure 1.3. Scheme of crop water requirement: If adequate rain is insufficient to meet crop water needs, additional water must be withdrawn from available groundwater or surface water. The additional “blue” water used in irrigated systems is often called the Net Irrigation Requirement, NIR. It is usually applied to the field using diverse methods such as drip, sprinkler, or surface irrigation. Irrigation is always accompanied by the estimate that about 50% of agricultural water withdrawals do not reach the crops because of losses in irrigation infrastructures (e.g., leaking and evaporating from irrigation canals and pipes). The total water withdrawal thus necessary to meet NIR is the Gross Irrigation Requirement (GIR), which includes the water losses in irrigation systems.

In this sense, good **irrigation management**, characterized by an efficient **irrigation system** and an appropriate irrigation strategy, is crucial in improving water use in agriculture. The **irrigation strategy** determines how much water to apply and when to irrigate. The decision of whether or not to irrigate an agricultural field, as well as the amount of irrigation



water applied, are complex decisions for producers, and depend on several factors (see Figure 1.3), being the most important the crop water requirements, the weather conditions and water infrastructure, as well as water losses (due to inefficiencies in application methods and malfunctioning of irrigation systems). Irrigation management may be improved by (i) the adoption of climatic forecast methods to predict and anticipate water needs, (ii) integrating efficient and precision irrigation systems (e.g., drip and micro irrigation systems), and (iii) by the increase of the **Water Use Efficiency (WUE)** and **Water Productivity (WP)** in the agricultural systems (see **Box-a** which illustrates the difference of these two concepts).

Particularly, *WP* refers to the amount of crop or food produced per unit of water used and is a useful indicator of sustainable water management in agriculture. It is found that any increase in yield achieved by eliminating or reducing non-productive water use will lead to an increase in *WP* (e.g., Brauman et al., 2013). The *WP* may be increased in cropping systems by:

- (i) **Improving varieties** or drought-resistant crops to enhance crop capacities to produce more yield with less water.
- (ii) **Improving WUE**, reducing outflows/losses in the distribution and application systems, and optimizing irrigation by precision irrigation methods.
- (iii) **Reducing crop water consumption** by directly reducing water applied or reducing the external factors that increase crop water requirement.

Concerning the first way to improve *WP* by substantially increasing yield without causing a corresponding increase in crop transpiration, efforts have been made. They are addressed by conventional **plant breeding** and, more recently, molecular biotechnology, e.g., by selectively transferring photosynthetic mechanisms from CAM and C4 plant species to C3 plant species (Muhie, 2022); or by increasing the resistances along the water pathway (Cui, 2021). Alternatively, spectrally selective modifications of the **radiative properties** of crop leaves have been proposed by Stanhill (1992) and were estimated to reduce the transpiration potential by at least 25% without affecting carbon dioxide assimilation.

The second approach focuses on reducing losses in water distribution and application. In this sense, **drip irrigation** has significantly contributed to higher *WP*, with **irrigation application efficiencies** reaching 90% or more, reducing significantly irrigation inputs (Cetin and Kara, 2019; Chouhan et al., 2014; Parthasarathi et al., 2018), but at the same time, increasing water deficit by rebound effects (water savings having favored the extension of irrigated areas). This implies minimal potential for further improvements of *IWP* in irrigation technology. However, the potential to increase *IWP* lies in the potential irrigated lands currently irrigated by other less efficient methods that may adopt drip irrigation technologies (which represent only around 5% of the global irrigated surface). Additionally, *WUE* in water conveyance and distribution systems is hardly improvable in many cases because of all the social and governance problems involved in their management (McNabb and McNabb, 2019).

The third option aims to reduce crop water consumption without a corresponding decrease in crop yield and without breeding or genetic engineering techniques, which may be controversial and expensive (in terms of money and time). This third approach will be more explored then. When water availability is limited, the most used method to reduce crop water consumption is directly reducing water applied below the optimal crop conditions. The

uncontrolled (or imposed) **Deficit Irrigation (DI)** indicates that water is supplied at levels below the **Actual Evapotranspiration** of the crop (*AET*) throughout the season, mainly caused by the cost of irrigation pumping and inadequate irrigation scheme capacity.

However, water reduction may also be applied to increase crop quality and water productivity in cropping systems, by the called **Regulated Deficit Irrigation** practices (RDI), which differ from **uncontrolled Deficit Irrigation (DI)** by the fact that in RDI, water is reduced by eliminating irrigations that have little impact on yield (i.e., allow some yield reduction with a significant reduction of irrigation water). RDI is typically applied during the low water-sensitive stages of the plant, at defined growth stages, or throughout the whole season (Cameron et al., 2006; Loveys et al., 2004). The success of RDI is based on physiological knowledge of the crop-specific yield responses to crop water stress and alternate drying and wetting cycles (Kang and Zhang, 2004; Marsal et al., 2002; Santos et al., 2003). The major disadvantage of the RDI is that it is required to maintain a plant's water status within narrow limits, which is difficult to achieve in practice.

RDI is largely implemented, mainly by partial root-zone irrigation, saving water up to 20 to 30% without or with a minimal impact on crop yield (Chai et al., 2015). Crops or crop varieties most suitable for RDI are those with a short growing season and are tolerant of drought. However, several **water-sensitive crops**, such as maize, wheat, cotton, potato, and sorghum, respond well to RDI practices (Steduto et al., 2012). This list may also include sunflower, bean, groundnut, soybean, and sugar cane, where reduced water is limited to (a) certain growth stage(s) (Kirda, 2002). For example, Stegman (1982) reported that the yield of maize, sprinkler irrigated to induce a 30% to 40% depletion of available water between irrigations was not statistically different from the yield obtained with trickle irrigation maintaining near zero water potential in the root-zone. Similar works have been carried out in other field crops, such as soybean (Eck et al., 1987; Specht et al., 1989), sunflower (Rawson and Turner, 1983) wheat (Musick and Dusek, 1980), and potato (Trebejo and Midmore, 1990), also showing slightly reductions on yield under RDI.

With other optics, water consumption may be reduced by reducing crop water needs by limiting evapotranspiration. **Evapotranspiration (ET)** is the process by which water is lost from the soil and plants through **evaporation** and **transpiration**. Limiting *ET* can be crucial in water-limited regions or during periods of drought, as it helps to conserve water and maintain soil moisture. In irrigated systems, (gross and net) irrigation requirements largely depend on the **Reference Evapotranspiration** of crops ( $ET_0$ ). Firstly, evaporation may be reduced by enhancing soil water content. Preventing surface runoff by increasing aggregate soil stability via soil amendments (Ben-Hur, 2006) and using conservation soil techniques such as trash lines (Wakindiki and Ben-Hur, 2004) or by field-surface tillage covers (Ben-Hur and Assouline, 2002) are traditional practices to increase the surface **water storage capacity of the soils**, increasing water availability and better infiltration to reduce evaporative losses. Also, experimental evidence suggests that significant reductions in water use can be achieved when **limiting soil evaporation** by using mulching techniques (Prosdocimi et al., 2016).

On the other hand, plant transpiration is the process by which water is lost from plants through the stomata of their leaves. While transpiration is essential for plant growth and survival, high transpiration rates can lead to crop water stress and reduced plant productivity. Several strategies can be used to prevent or **reduce plant transpiration**. Besides plant genetic manipulation, **regulating air temperature and shading** are the most used techniques to



reduce crop transpiration. Artificial (non-spectral selective) reflectants showed some success, such as kaolin applied to sorghum (Stanhill et al., 1976), but its applicability is limited to research purposes and thus without impact on a larger scale.

The advantage of shading techniques is that they also reduce soil evaporation, especially during the **hottest period of the day**, representing a key action to save irrigation water and to improve *WP* and *IWP* (e.g., (Kitta et al., 2014; Mahmood et al., 2018; Möller and Assouline, 2007). However, it is fundamental to quantify the effectiveness of **partial coverage** and find the optimal partial coverage which causes a significant amount of water saving without adversely affecting the crop yield.

There are basically three ways to provide shade to crops: (i) **intercropping systems** (natural shading), e.g., that provides mutual shading with taller crops or trees, (ii) **artificial shading**, e.g., from installed shade cloths, shade sails, or other “constructed” shading structures and (iii) **urban shade** (in urban agriculture), from buildings, or other “existing” structures that can help to reduce sunlight and heat exposure. The innovative AgriVoltaic systems, which represent an alternative to reduce crop evapotranspiration (and save water in limiting conditions) by controlled shading, are introduced and developed in the next section.

#### 1.4 AGRIVOLTAIC SYSTEMS: FROM ENERGY TRANSITION TO CROP PROTECTION

The urgent need for an energy transition to face the significant impact of fossil fuel emissions on global warming (Lamb et al., 2021) have impulse recently the use of **renewable energies**, especially the production of “clean energy” from solar technologies. In 2016, renewable energies represented roughly 23% of the world's electric production – 27.7% of the electric production capacity – and nearly 59% of the newly set up capacities. This evolution occurs in the context of several geopolitical tensions associated with energy and climate change.

Theoretically, **solar energy** possesses the potential to adequately fulfill the energy demands of the entire world if technologies for its harvesting and supplying were readily available (Blaschke et al., 2013). The average amount of solar energy received in Earth's atmosphere is around  $342 \text{ W m}^{-2}$ , of which ca. 30% is scattered or reflected to space, leaving ca. 70% ( $239 \text{ W m}^{-2}$ ) available for harvesting and capture (Hart, 2015).

Among solar energy-harvest technologies, **photovoltaic (PV) technologies** are considered one of many key solutions for fulfilling a worldwide growing demand for clean energy and reducing global carbon emissions (Jones et al., 2017a). New technologies are being employed to increase the electricity generation from PV energy centrals at phenomenal rates. Solar PV remains the fastest-growing **renewable energy**, representing over half of all the renewable capacity installed internationally. In a new dawn for the sector, global installed solar generation capacity reached the terawatt frontier in the spring of 2022 (IEA, 2023), while in 2004, it was only 3.7 GW (Kabir et al., 2018). Solar PV capacity is expected to almost treble over the 2022-2027 period, growing by 1.5 TW and **surpassing coal** as the largest source of power capacity worldwide (IEA, 2023).

Despite the legitimacy of this development, solar energy is confronted with several **barriers**: high initial installation costs, lengthy payback periods and small revenue streams, performance limitations of some components such as batteries, availability of materials for PV panels fabrication, maintenance, inspection, repair and evaluation of solar power systems. The **rapid growth** of PV energy requires huge plots to generate large-scale solar power, particularly in rural areas (Poggi et al., 2018). In the context of growing **land scarcity** and in which land is currently in use for other purposes (the production of food is the most important considering the increasing food demand), competition for **access to new surfaces** is a major obstacle to PV implementation (Nonhebel, 2005). Indeed, the extensive installation of large-scale ground-mounted PV facilities has led to their establishment on agricultural land, increasing concerns about the **loss of arable surfaces** for more profitable PV energy production and increasing competition for land with agricultural production (Schindele et al., 2020).

The majority of ground-mounted solar energy plants built to date on open areas have been designed by photovoltaic installers without prior consultation with local actors and professionals to ensure the control of environmental impacts and acceptance and without exploring the possibilities offered by **synergistic systems** of food and electricity production, to limit socio-economic conflicts or with other land uses, which can be of significant concern, especially in regions with limited land area or a dense population. In this sense, public opposition to ground-mounted PV rises, as well as the interest in new integrated systems that might offer a solution for these regions, reducing the competition between food and energy.

In this context, in the last decade, the concept of integrating solar farms with crops for energy and food production, proposed for the first time by Goetzberger and Zastrow (1982) and currently called **AgriVoltaic systems (AV)**, has received considerable attention around the world (Mamun et al., 2022; Pascaris et al., 2020), with the promise of address the associated land conflicts (Elborg, 2017), but also providing **crop protection** face to high solar radiation and elevated temperatures (with the potential to reduce water needs by the way), by smart management of these systems. Nowadays, it has been demonstrated that AV systems can enhance land productivity, producing food and reducing soil occupation (Dupraz et al., 2011). Since then, some studies have assessed the technical feasibility of AgriVoltaic systems and their potential economic benefits and social acceptance (Dinesh and Pearce, 2016; Pascaris et al., 2021). In this sense, it has been estimated that solar production would offset the global energy demand if even less than 1% of cropland were converted to an AV system (Adeh et al., 2019). Also, economic evaluations have shown that AV systems can increase farms' incomes by over 30% if yield losses through shading effects are minimized by selecting suitable crops (Mavani et al., 2019).

Currently, AV systems have been significantly implemented in many parts of the world. These first AV systems were based on fixed-supported structures (**Fixed AgriVoltaic systems - FAV**) used to raise the solar panels about 4 – 5 m above the ground, allowing farm machinery to access the crops below. More recently, controlled tracking systems (which consist of adding a tracker mechanism to make the PV panels orientable by rotation around their fixing axis) have been developed to control the radiation transmitted under the structure (Amaducci et al., 2018; Valle et al., 2017). In this sense, the called **Dynamic AgriVoltaic systems (DAV)** have been used to improve the compromise between electricity production objectives and the physiological needs of plants. Other solutions include solar greenhouses or photovoltaic modules installed between crop rows.

The high interest in these systems has led to the development of several **AV operational projects**, mainly in countries such as France, Germany, Italy, the United States, and Japan (with more countries joining this trend). The AV power installed worldwide has experienced tremendous growth in recent years, achieving a worldwide installed capacity exceeding 2.9 GW by 2020, while it was only 5 MW in 2012. Only in France, the announcement at the end of December 2020 by CRE (Commission de Régulation de l'Energie) of 31 new agrivoltaic projects and the “Cultivons Demain” Initiative (expecting to equip 300 French farms by 2025) confirms the public authorities' interest in this innovative solution for agriculture.

It was not until 2011 that the concept of AV evolved and received more interest from agronomical research to study the mutual **benefits between crops and PV panels** (see Figure 1.4) with the first AV works carried out in France (Marrou et al., 2013a,b,c) to study the benefits of shading from AV systems on crop growth and water used for lettuce, cucumber, and durum wheat. This first work demonstrated that the coexistence of renewable energies and agriculture is possible. Since AV systems have been evaluated with similar results for multiple crops, many crops (e.g., alfalfa, broccoli, cassava, hog peanut, lettuce, mustard greens, and sweet potato, according to (Trommsdorff et al., 2022)). Another agronomic benefit of using panels over crops is their barrier function against **high solar radiation, heat, drought, or heavy rainfall**. Some authors have focused their interest on the side effects of AV systems on the water budget for crops (e.g., Elamri et al., 2018a,b analyzing the effect of the rain distribution by panels and their impact on water budget).

Shading from the panels can help keep the soil moisture longer by **limiting crop evapotranspiration**, providing plants with the optimum water supply, and **increasing WP** (e.g., Barron-Gafford et al., 2019). Additionally, **rainwater harvesting** may be integrated into the AV systems (e.g., Chekired et al., 2022) to store water for irrigation periods. Water-limited areas (which will become more water-stressed in the coming years) are most likely to benefit from AV systems as shading management may reduce the reference evapotranspiration and consequently the water demand, reducing the negative effects of water stress.

In the particular case of **field crops**, they may benefit from AV systems on two fronts (i) by potentially **reducing the effects of droughts** on crop production and (ii) by potentially producing higher electricity in these high-radiated areas. Their cultivation under AV systems may be an interesting option for developing countries where irrigation infrastructure is insufficient or inexistent (maize grown in rainfed conditions) and where the need for energy is urgent, matching both necessities (crop protection and energy production).

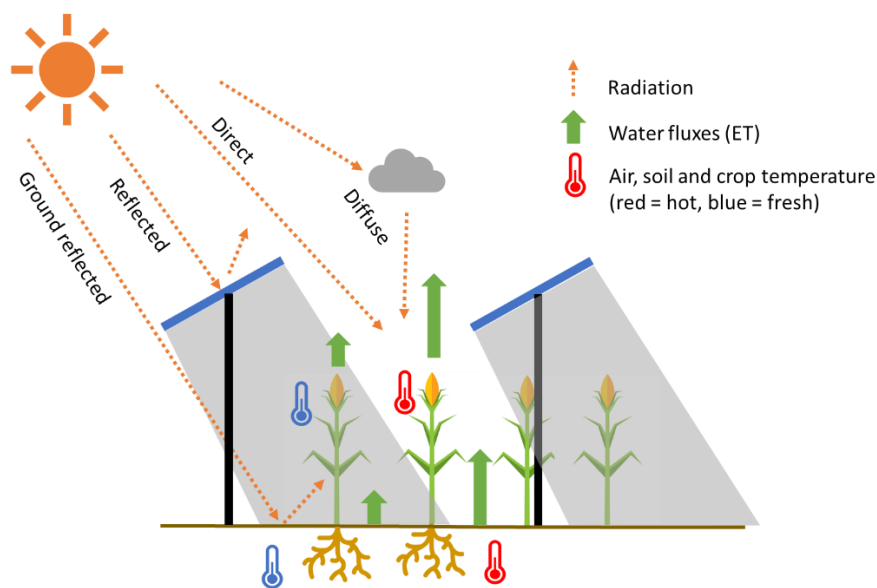


Figure 1.4. Scheme of Agrivoltaic Systems and their main effects protecting crops from radiation and heat stress and reducing water consumption.

However, the coexistence of PV panels and crops also implies a “sharing” of light that can affect crops. It may differ depending on (i) the crop-specific tolerance to shade, (ii) the features of the AV system (with fixed or dynamic PV panels), and (iii) the characteristics of the PV panels (density, height, transparency, and geometry). An interesting and unexplored axe of research is focused on the **optimization of DAV systems for both crop yield and water resources**. Controlling the rotation of panels in DAV systems may help to reduce or avoid water but also may permit to modify the spatiotemporal patterns of shade in favor of crops (unlike a fixed device), giving the possibility to, for example, fit the water and light needs of a given crop at a time “*t*” of the day or a day “*i*” of the season.

This optimization poses complex difficulties, especially the **short-term (e.g., hourly)** and **long-term (e.g., daily-monthly)** radiation variations under DAV systems could cause shade-induced crop yield loss and spatial soil moisture heterogeneities, among other physical and physiological effects. Not only available radiation for crops is modified by the presence of PV panels in AV systems, but also other weather variables such as temperature, relative humidity,

wind speed, and distribution of rainfall can be affected in complex ways, impacting crop status (Boken, 2005).

Constraints on water management (resource availability, irrigation, water harvesting) will undoubtedly exist. Particularly, shade patterns under AV question the principles of control of irrigation systems at different horizons (short for **real-time control**, long for the optimization of overall performance), and the performance achievable with the implementation of methods relating to precision irrigation must be considered for simulations. The water balance of the soil and plant growth indicators must be described and modeled by dedicated and new processes, therefore with associated issues of standardization and definition of good practices.

Thus, it is crucial to understand the interplay between water needs and shade tolerance of crops to fit the plant needs to the environmental conditions and allow them to grow unaffected by seasonal changes or at critical phenological phases of the crop that may be sensitive to shade. In particular, growing field crops under **shade conditions** represents a challenge because these are annual crops with a life cycle of 3 to 5 months, presenting a complex physiology and diverse responses to radiation (C3 or C4 type metabolism). Thus the effects on crop growth development and water budget remain to be explored in more detail for these crops.

From this perspective, **modeling tools** will help analyze the possible scenarios regarding crops, techniques, and irrigation practices. The advances in modeling **agroforestry systems** (shaded systems intercropping crops and trees, Talbot, 2011) may inspire the **modeling approach** for AV systems. Chapters 3 and 4 will present a detailed state of the art to (i) understand better the separated effects of water stress and shade on field crops, aiming to obtain knowledge to explain their combined effects in AV systems (Chapter 3) and (ii) analyze the possible adaptations of crop models that may permit to simulate crops in AV systems for optimization and operational purposes (Chapter 4).

**Box-a. WUE vs WP**

Water use efficiency (*WUE*) and water productivity (*WP*) are two different terms. However, “water use efficiency” terminology has been at the center of debate for many decades due to differing perspectives in defining it across various disciplines, particularly engineering, irrigation, crop agronomy, and crop physiology. The fact is, both terms do exist, and both have different definitions and applications. This confusion in agronomy and crop science is mainly associated with the relationship between biomass production and water consumption. The concept of **water use efficiency** seems ambiguous as it is sometimes a confusing concept; *WP* is a straightforward and easy-to-understand term. The simple definition of efficiency in daily life is a ratio or percent (Kilemo, 2022). In water sciences, the term *WUE* reflects the output-to-input water volumes ratio and is widely used in irrigation systems engineering design, evaluation, and management. These efficiencies are expressed in percentage (%) with a maximum value of 100%. Values less than 100% imply water losses during the process. In agronomy, the *WUE* metric should simply measure the efficiency of the system in making water available to the plants, measured as the ratio of water available to the plants (root zone) to water supplied from the source, without considering the benefit (yield) produced from the applied water (Seckler et al., 2003). Thus, *WUE* (for a crop) is defined as:

Equation 1-1

$$WUE = \frac{AET}{I + R}$$

Where *WUE* is the water use efficiency ( $\text{m}^3 \text{m}^{-3}$ ), *AET* is the actual evapotranspiration of the crop ( $\text{m}^3$ ), *I* is the effective irrigation ( $\text{m}^3$ ) and *R* is the effective rainfall ( $\text{m}^3$ ). In this equation, *AET* may be replaced by plant transpiration (*T<sub>p</sub>*, in  $\text{m}^3$ ) if evaporation is neglected.

Thus, while the *WUE* term should be used to describe the effectiveness with which the water supplied in the field is used for plant growth or evapotranspiration, the **water productivity** concept concerns the biomass outputs or economic value of those outputs produced from the use of the water applied or consumed by crops. Thus, the definition of *WP* in agronomy makes it possible to evaluate the efficiency of the process by which water is consumed by the plant to produce biomass (Doorenbos et al., 1997). It is used to describe the relationship between the yield of the plant and the amount of water used for it. Generally, the water consumed is assimilated to the evapotranspiration of the crop accumulated during its development cycle. Thus, crop *WP* is generally defined as follows:

Equation 1-2

$$WP = \frac{Y}{AET}$$

Where *WP* is the water productivity ( $\text{t m}^3$ ), *Y* is the crop yield ( $\text{t ha}^{-1}$ ) and *AET*, is the actual evapotranspiration ( $\text{m}^3 \text{ha}^{-1}$ ). In irrigated conditions, it is possible to evaluate the irrigation strategy applied by calculating the **water productivity of irrigation** (*WPI*) (Khila et al., 2016):

Equation 1-3

$$WPI = \frac{Y}{I}$$

Where *WPI* is the water productivity of irrigation ( $\text{t m}^3$ ), *Y* is the crop yield ( $\text{t ha}^{-1}$ ) and *I* is the total irrigation water volume used during the cropping season ( $\text{m}^3 \text{ha}^{-1}$ ).

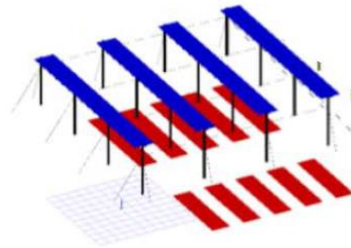
In conclusion, both concepts (*WUE* and *WP*) have many facets and are frequently used indiscriminately. The recent literature shows that what was previously wrongly defined as *WUE* was renamed *WP* in the early 1980s. This thesis will use the concepts described above, replacing the term *WUE* with *WP* when misused in the cited literature.



# CHAPTER 2

## GENERAL METHODOLOGY

*“In theory, theory and practice are the same. In practice, they are not.” — Albert Einstein*







## CHAPTER 2 – GENERAL METHODOLOGY

### 2.1 APPROACH AND RESEARCH AXIS

The approach of this thesis is based on two research axes: the first one concerns the description of the independent and combined effects of water deficit and shade on the growth and development of field crops by existing bibliography and by field experiments of a crop grown under real AgriVoltaic conditions. The theoretical approach of axis 2 targets the modeling of field crops under AgriVoltaic conditions by the analysis of the processes affected by shade in generic crop models, and the practical approach of axis 2 relies on the analysis of a case study using a simple model to simulate a crop grown under AgriVoltaic conditions, with and without water deficit.

Thus, axis 1 complements axis 2 by (i) providing the understanding of concepts associated with both independent stresses (by the existing bibliography) and (ii) characterizing the effects of independent and combined water and shade deficits under AgriVoltaic conditions (by experiments), describing the specific heterogeneities on water flows.

Therefore, axis 1 coupled with the theoretical basis aborded in axis 2 (describing different methods used in generic models that may permit to consider of shade in AgriVoltaic systems), allows the identification of the key generic processes affected by shade that may be targeted to improve the modeling of crops under both limiting conditions (water and radiation) in the specific case of AgriVoltaic systems. The application approach of axis 1 (field experimentations) provides the data required for the application approach of axis 2 (case study). Figure 2.1 schematizes the general approach and shows the connections between the two axes.

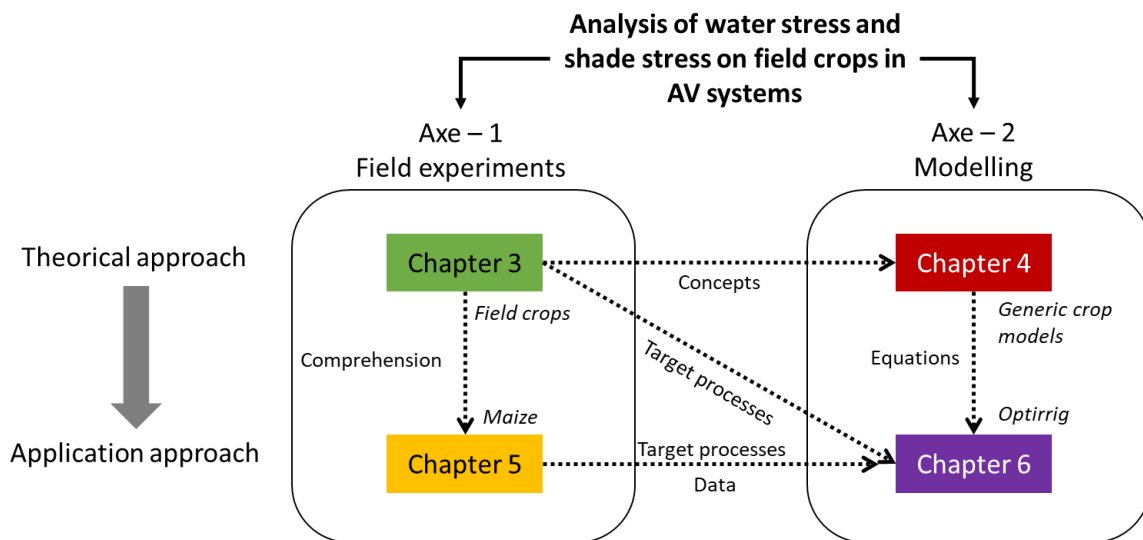


Figure 2.1. The general approach, axes of research, and relationship between the different Chapters in the thesis

## 2.2 STUDY PERIMETER

For **axis 1** in this thesis, the **theoretical approach** focuses on the study of **field crops**, investigating the general effects of **water stress** and **shade** on annual crops during their crop cycle, which differs from horticultural or perennial crops. Consequently, bibliography research targeted only experiments on the most common field crops, differentiating (when possible) between C3 and C4 metabolisms and referencing other species when there was no bibliography for field crops.

The **application approach** of **axis 1** relies on **experiments** growing a **maize crop** in AgriVoltaic systems during three consecutive annual cropping seasons. Maize crop (*Zea mays var. Ixabel*) was selected from other field crops because of (i) its high sensibility to water and radiation deficits (giving the possibility to quantify their effects on production and water use) and (ii) its global importance around the world as a main source of food and raw material supplier (see **Box-b**). The experimental platform and the methodology implemented to characterize the impact of PV panels on the crop grown and water balance under the studied AgriVoltaic systems will be presented in Chapter 5. Firstly, the different devices are described, and then the experimental protocols to estimate crop growth and water balance, as well as the weather monitoring, detailing the measurements and instrumentations.

Concerning modeling **axis 2**, the **theoretical approach** is limited by the "**generic crop models**," which are based predominantly on simple functions and empirical representations of plant processes involved in crop growth and development. However, some examples and equations regarding the more complex models are mentioned or described if they represent an opportunity to improve the generic crop models to consider shade effects on crop processes or to improve the simulation of combined water and shade stresses. For the **application case study** of modeling, the Optirrig model was chosen because of (i) its proven capacity to simulate field crops under non-limiting conditions and (ii) its simple structure, giving the possibility to adapt the model in a "parsimonious" by seeking "the simplest possible complexity" integrating empiric equations without over-complexify model and without increase the "running-cost." The inclusion of complex mechanistic models was just advocated in the theoretical approach of axis 2 (but excluded in the case study). The model used in the case study is described and analyzed in Chapter 6, as well as the methodology used for the case study.

### 2.3 ORGANIZATION OF THE THESIS

In the present manuscript, **Chapter 1** –Background introduced the current background about water stress, irrigation management, agriculture (focused on field crops), and their nexus with AgriVoltaics systems. This chapter aims to introduce a general context to understand the research questions addressed in this work and introduce the main concepts and definitions used in the following chapters. **Chapter 2** – General Methodology presented the general methodology and the axes of research, followed by the study of the effects of water deficit and shading on maize.

Next, **Chapter 3** – Water and Shade stresses on Field Crops—state of the art presents a bibliography synthesis of several studies characterizing the effects of water stress and shade (shade stress) on crop growth and development and water use, focusing on main field crops (particularly maize). This chapter aims to understand better the crop responses to water stress and shade independently and further explain the combined effects studied by experimentations presented in Chapter 5. Also, this chapter defines the concepts of water and shade stresses and includes a description of the main shading patterns generated by different AgriVoltaic systems.

**Chapter 4** – Modeling Shade and Water stress in AgriVoltaic Systems: examines the key crop processes affected by shade related to the vegetative development, biomass growth, and water use of annual crops with the optics of “parsimonious crop modeling.” This chapter proposes simple modifications that may be implemented to consider the effect of shade in field crops modeling under AgriVoltaic systems. For this, different mathematical expressions involved in radiation use and water budget in generic crop models are explored, focusing on those that may be “easily” used as adaptations in simple crop models. This chapter also presents brief state-of-the-art modeling efforts realized to simulate crops under shaded conditions (in agroforestry systems and, more recently, in AgriVoltaic systems).

Next, the results of the field experiments are presented in **Chapter 5** – Effects of Shade and deficit Irrigation on Maize growth and development under AgriVoltaic systems. The main results presented are the independent and combined effects of water deficit (deficit irrigation and not irrigated conditions) and shading (from specific “fixed” and “dynamic” AgriVoltaics systems in the site) on crop development (phenology and vegetative growth), crop production (biomass and yield) as well as on water budget (irrigation, evapotranspiration, and leaf gas exchanges). This chapter is built mostly on results published in the *Agricultural Water Management* journal (Ramos-Fuentes et al., 2023). Also, this chapter includes the methodology associated with the field experiments. They have described the experimental site, the instrumentation, and the protocols to obtain data.

**Chapter 6** –Modeling Maize crop under Dynamic AgriVoltaic Systems: a case study presents a case study testing different simple adaptations of a generic crop model to simulate the maize crop growth in the dynamic AgriVoltaic system of Lavalette during 2020 and 2021, considering both water comfort and water stress conditions. An analysis and a framework to adapt the model to shade conditions are proposed at the beginning, and after the modeling results are presented and discussed. Finally, **Chapter 7** – General Discussion and Perspectives discusses the general ideas of the thesis, going forward in the analysis in the preceding chapters; and **Chapter 8** – General Conclusions presents the general discussion of this thesis work.

### Box-b. Maize crop (*Zea Mays L.*) phenology

#### Maize cropping

Maize is a summer cereal grown between May and October in the Northern Hemisphere, so it is sown between mid-April and late May, having a growing cycle ranging from 3 to 6 months. Their leaves range from 8 to 20 and are present alternatively on nodes and reach from a 1 to 3 m height for the cultivated varieties. The maize crop is highly water-consuming during its growing season, and yield is thus highly correlated to water inputs (Oury, 2010). Also, as a C4 plant, the carboxylation pathway of maize photosynthesis strongly correlates with solar radiation (Berry, 1970). Therefore, sufficient solar radiation can promote the high yield of maize and vice versa.

#### Maize phenology

Its whole growth period can be divided: into the seedling stage (conventionally two weeks), heading – or vegetative – stages (conventionally four weeks), reproductive stages (conventionally four weeks), and maturity stages (conventionally four weeks). A more detailed description will be provided in Chapter 3.

The early vegetative period is called the "withdrawal" period and lasts until the emission of the first leaves. Next, maize is characterized by rapid growth during which its entire leaf surface is initiated and established. This rapid growth requires summer temperatures (between 20 and 30°C) and significant water supplies. The reproductive period starts with the rapid elongation of the internodes. Then begins the flowering, characterized primarily by the emergence of male panicle, approximately one week before pollen dispersal (anthesis), and female flowering: the emergence of silks. The reproductive period finishes thus with fecundation. Then starts the maturity with the grain filling stages, which are essentially characterized according to the development of the albumen, where 3 phases are distinguished. The first corresponds to the period of seed tissue differentiation during which cell division is predominant. This phase lasts about 15 days after fertilization. The second corresponds to the loading phase of the grain in carbonaceous assimilates and to the linear phase of grain biomass growth. Finally, the third phase corresponds to the physiological maturity phase and is characterized by the reduction in the accumulation of biomass and reduced water content. The grain usually matures between 50 and 60 days after fertilization.

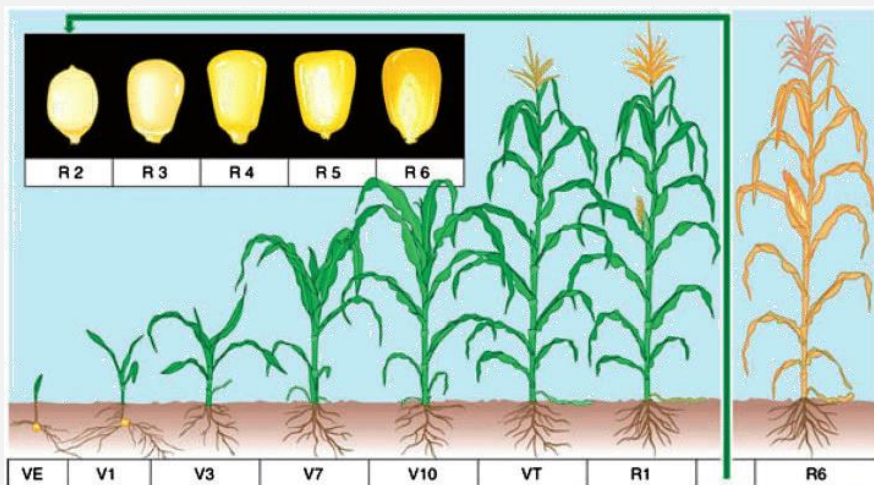


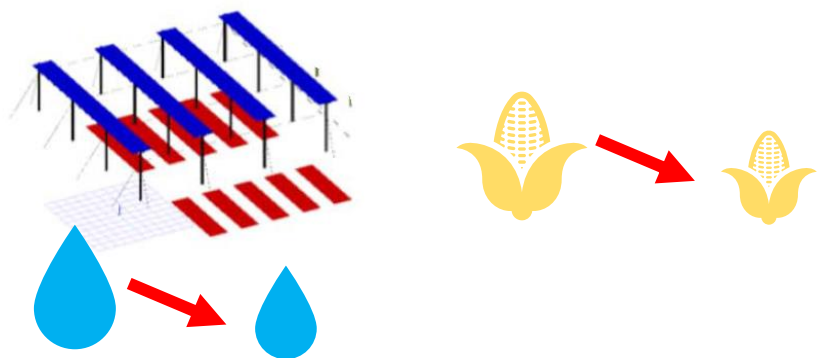
Figure 2.2. Different growth stages of a maize plant, including vegetative (V) and reproductive stages (R). The V developmental milestones include emergence (VE), in which the coleoptile reaches the soil surface and elongates due to its exposure to sunlight; V1, in which the lowermost leaf has a visible leaf collar; V3, in which the plant has three leaf collars, whose growth purely relies on photosynthesis; V7, in which the plant has seven leaf collars and experiences rapid growth; V10, in which the plant equipped with ten leaf collars has a rapidly-growing stalk and VT, in which the last branch of the tassel is visible. The R developmental milestones include R1, in which any silk is visible outside the husk; R2, in which kernels are white and resemble a blister in shape; R3, in which kernels are yellow on the outside with a milky white inner fluid; R4, in which starch is dough-like consistency; R5, in which kernels are dented and R6, in which all kernels on the ear have reached maximum dry weight with physiological maturity—source: (Zhao et al., 2012).

# CHAPTER 3

## WATER AND SHADE STRESSES ON FIELD CROPS—STATE OF THE ART

*“Water is the driving force of all nature.” — Leonardo da Vinci*

*“The Sun is the giver of life”. — Ramses II*





## CHAPTER 3 – WATER AND SHADE STRESSES ON FIELD CROPS—STATE OF THE ART

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In this chapter, the main purpose is to cover various aspects related to the effects of shade and water stress on field crops, in order to:

- (i) Provide a comprehensive overview of the independent effects related to water and shade stresses on field crops, by reviewing existing research and highlighting gaps in knowledge.
- (ii) Contribute to a better understanding of these stresses and provide elements of discussion about the potential effects of combining shade and water stress in AgriVoltaic systems.

The chapter will address aspects related to water stress, such as the importance of water for crop growth and development, the factors influencing water availability in agricultural systems, the mechanisms by which crops respond to water stress, and the potential consequences of water stress on crop productivity and yield. Similarly, the chapter will address shade stress, which refers to the reduced radiation availability that can occur due to factors like canopies of other plants or structures covering the crop.

This chapter explores the effects of shade on crops, including the impacts on phenology, growth, yield and water use, but also addresses the effects of shading on the most relevant agrometeorological variables and discusses the different shading patterns generated by different AgriVoltaic systems.

Hence, this chapter seeks to contribute to a better understanding of the experimental results presented in Chapter 5 and provide a foundation for the choices in selecting the key processes considered in adapting the Optirrig model in the case study presented in Chapter 6.



### 3.1 INTRODUCTION – PLANT RESPONSES TO ABIOTIC STRESSES

Abiotic **stress** is an environmental factor that induces a potentially injurious strain in living organisms. In cropping systems, plants respond and acclimate to external biotic and abiotic factors in the **soil–plant–atmosphere continuum**. When one of the factors is limited enough or “excessive” to cause a significant hurdle in attaining the potential yield, we say that the crop is experiencing **crop stress**. Crop stress is usually expressed by several morphological and physiological alterations and influences biochemical processes, leading to changes in plant growth and development (Anjum et al., 2011; Farooq et al., 2009). The most common abiotic stresses in cropping systems affecting plant growth and development are temperature, radiation, water status, and available nutrients (Charles-Edwards, 1982; Heins et al., 1998).

Finding an approach to sustain high yields of crops under biotic and abiotic stresses is an important goal of agriculture researchers and stakeholders alike. Identification of **yield limiting factors** in the soil–plant–atmosphere continuum is the key to improved management of crops under **limiting constraints**. Particularly, with the advent of AV technologies in cropping systems (inducing a crop “shade stress”) and climate change intensifying extreme heat and droughts (increasing crop water stress), the study of this both limiting factors (separately and together) is becoming more critical for the large-scale adoption of these new technologies. For this, it is necessary to identify and characterize the different crop responses to detect and understand the common mechanism for these **bi-factorial stress conditions**.

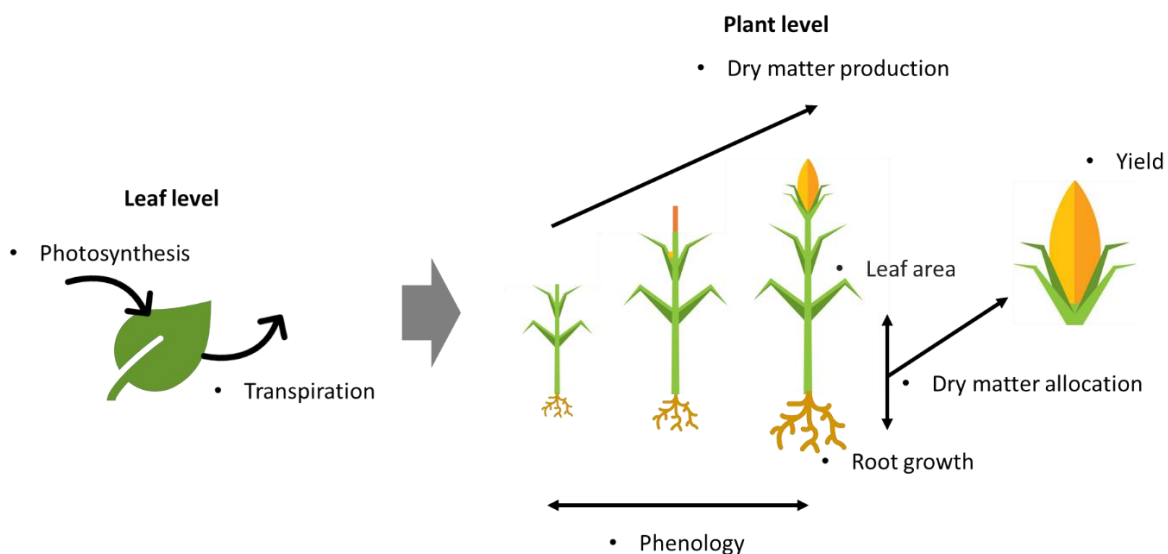


Figure 3.1. Main variables affected by plant stress at leaf and plant level.

Both water stress and shade affect a wide range of physiological, cellular, and molecular plant processes. The plant reactions to stress can be separated into **leaf-level responses** (physiological and biochemical responses in the short-term timescale) and **plant/crop-level responses** (morphological and agronomical impacts in the long term). The main leaf-level responses are related to intracellular processes and include modifications on **photosynthesis** (net assimilation rate, chlorophyll content, photochemical efficiency), **stomatal conductance** (gas exchanges of CO<sub>2</sub> and H<sub>2</sub>O via the stomata), and maintenance of cellular metabolism and membrane stability turgor through **osmotic**

**adjustment**, among others. On the other hand, the cumuli of leaf-level responses and their maintenance over time lead to long-term effects at the plant/canopy level, mainly associated with dry-matter partitioning and production (reduction of leaf area and alterations of root/shoot ratio). The timing of specific **phenological** stages and developmental processes are typically modulated by day length and crop temperature. This timing can be altered by stress factors such as limited water, radiation and nutrients. The main variables affected by these responses are schematized in Figure 3.1.

In cultivated plants, the physiological basis of dry matter and yield production is commonly explained by the **source-sink** concept (see Figure 3.2), where the source is the potential capacity for photosynthesis (leaves), and the sink is the potential capacity to utilize the photosynthetic products (Smith et al., 2018). If the source is limited, the sink cannot be high, even if the sink is large. **Abiotic stresses**, such as water stress, prolonged shade, temperature extremes, nutrient deficiencies, and salinity, can significantly affect the source-sink relationship in crop growth (Sonnewald and Fernie, 2018). Here are some ways abiotic stresses impact this relationship:

- (i) **Reduced source size:** Abiotic stresses reduce the size of the organs capturing the energy for photosynthesis. Abiotic factors such as radiation, water, and temperature regulate the growth of leaves, the leading source organ.
- (ii) **Reduced source capacity:** Abiotic stresses can impair the photosynthetic capacity of leaves, leading to a decrease in the source capacity. High solar radiation, for instance, can damage photosynthetic machinery and decrease carbon assimilation capacity.
- (iii) **Decreased source intensity:** Abiotic stresses can disrupt the physiological processes involved in photosynthesis, reducing source intensity. For example, water stress can cause stomatal closure, reducing the inflow amount of carbon dioxide for photosynthesis and limiting the intensity of produced assimilates.
- (iv) **Shortened source duration:** Abiotic stresses can accelerate leaf senescence, reducing the source's active photosynthetic period duration. This can occur due to water stress, nutrient deficiencies, or extreme leaf temperatures. The shorter lifespan of leaves limits the time available for assimilating production.
- (v) **Altered source-sink balance:** Abiotic stresses can disrupt the balance between source and sink activities. For instance, under severe water stress, carbohydrate allocation may shift towards maintaining essential plant functions, diverting resources from yield formation. This altered balance can impact the distribution and utilization of assimilates.

The source-sink interactions, in addition, are controlled by genetic traits and physiological adaptive mechanisms, which vary with species and cultivars (**C3 and C4 photosynthesis** – see **Box-c**).

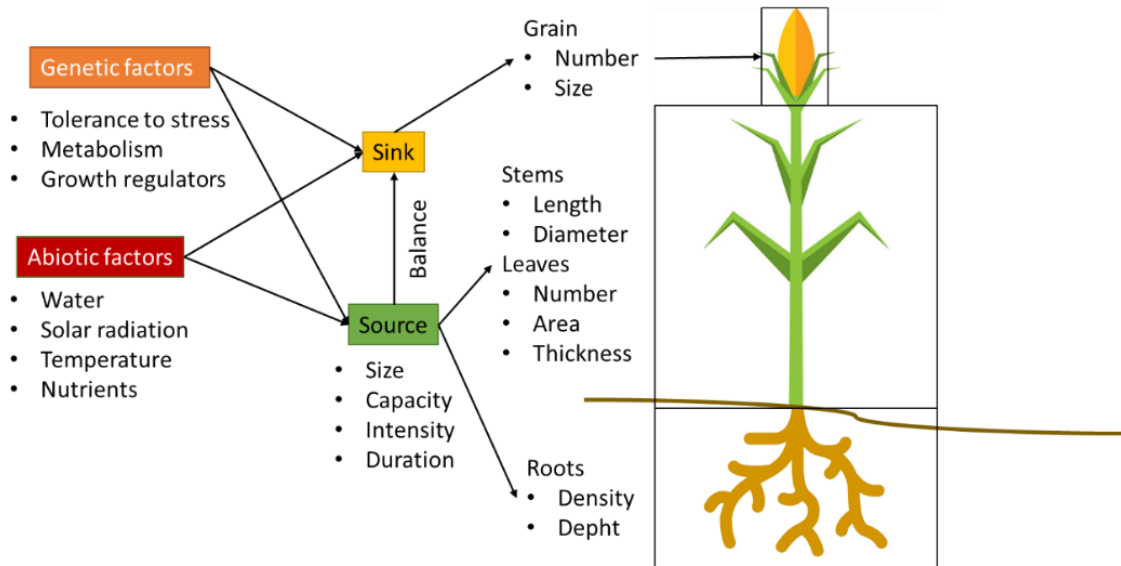


Figure 3.2. Schematic of the source–sink relations of a maize plant.

Understanding and managing the effects of abiotic stresses on the source-sink relationship is crucial for optimizing crop growth and yield under challenging environmental conditions, particularly shade and water stress in AV systems. A synthetic research bibliography of the separate effects of water and shade stresses on crops is presented in this chapter, focusing on maize and other important field crops for reference. The effects are separated into (i) phenology, (ii) vegetative growth and biomass, and (iii) yield. In the case of shade stress, the effects on microclimate are also included. The reader is invited to go directly to the resume section (Section 3.4) if this chapter's content is outside his interest.

## 3.2 EFFECTS OF WATER DEFICIT ON CROP GROWTH AND DEVELOPMENT

### 3.2.1 Crop water stress concept

Among the major abiotic stresses in agriculture, crop water stress (often called drought in literature) is one of the most adverse factors for plant growth and productivity worldwide (Noorka and Tabasum, 2015). In nature, plants do not respond very strongly to relatively short periods of water stress, as water availability often depends on rain events (which are unpredictable). In some specific cases, **mild water stress** could even push the plant to increase in WP (i.e., in winter wheat, Zhao et al., 2020). Thus, the effects of water stress are more evident under **severe water stress**, and the response will depend on the **specific-crop tolerance**. For example, sorghum is considered drought resistant, especially compared to maize. At the same time, soybean and maize can thrive better under water stress than rice (Tanguilig et al., 1987). Other crops, such as cotton, show complex responses to water stress because of their deep root system and ability to maintain low leaf water potential and regulate leaf turgor pressure osmotically.

**Crop Water Stress (CWS)** can be defined in various ways, for example, based on environmental factors or plant-based metrics. CWS is often defined as crop experience when the demand for water is not met by the soil water reserve supply, either by rainfall or irrigation inputs, during periods of high evaporative demand of the atmosphere associated with higher ambient temperature and vapor pressure deficit. However, this definition does not consider plant responses. In this sense, CWS considering plant water status could be defined as the situation in which plant water potential and turgor are reduced enough to interfere with the plant's normal functions (Dhakar et al., 2018).

Rapid and accurate detection of CWS is one of the most important issues of sustainable water management to prevent yield loss and optimize irrigation strategies. There are various conventional CWS indicators for determining crop water status, each with advantages and disadvantages. The main and widely used are soil-based, such as the direct measurement or estimation of **Soil Water Content (SWC)** and **Soil Water Potential (SWP)**. Both may be used to determine a “soil moisture stress” frequently correlated to CWS by simple thresholds, according to the soil properties, e.g., the percentage of the available soil water in the root zone (ASW) (Lehmann et al., 2013). Other indicators are based on evapotranspiration values, such as the **Evaporative Stress Index (ESI)** (Anderson et al., 2011) or combining both transpiration and soil moisture, such as the **Soil-Transpiration Factor (STF)** (Ritchie, 1998) or the **Soil Transpiration Efficiency (STE)** (Sinclair, 2012).

However, CWS is a dynamic and long-term accumulative process that develops gradually, affected by the different environmental factors (and their duration) related to CWS. Thus, only the soil water status or the climatic demand cannot explain the degree of CWS without considering more cumulative stress information from physiological and ecological factors (even if these methods are effective). Using crop physiological and ecological indicators to determine current **plant water status** can more directly and accurately identify CWS. Indeed, according to Zhang et al. (2021), plant-based CWS detection could save more water in irrigation schemes than soil-based metrics.

Many of these **plant-based indicators** are based on direct plant reactions (Khorsand et al., 2021); the main ones are leaf water content, leaf water potential, canopy water potential, sap flow monitoring in stems, leaf temperature – or other organs temperatures –, stomatal

conductance and stomatal resistance. Among them, leaf water content, canopy water potential, and stomatal conductance are the most effective plant-based metrics to characterize CWS (El-Hendawy et al., 2019; Zhang et al., 2021a).

The application of **thermal-based indices** involving leaf or canopy temperature to characterize CWS has increased in the last decades, replacing other methods in research studies and for irrigation schedules in practice because they are easier to observe and are less time-consuming (notably compared to the water potential and stomatal based methods). The principal part of the plant measured in temperature-based indices is the leaves because they are the most important organ in plant assimilation and transpiration and the most sensitive organ to water stress (Czajkowski et al., 2009). However, for CWS detection, **canopy temperature** measured by thermography or by infra-red (IR) thermometry is more practical since it is highly correlated to leaf water potential (Hackl et al., 2012), and, compared to leaf temperature, it integrates the thermal radiation from all plant and soil exposed surfaces in the field of view of the instrument into a single measurement. However, canopy temperature alone is insufficient to estimate crop water status. For this reason, many researchers have attempted to normalize the canopy temperature to account for the influence of other variable microclimatic parameters like vapor pressure deficit, air temperature, wind speed, and solar radiation.

The main thermal-based indexes are the summation difference between canopy temperature and air temperature (the first thermal index to quantify CWS), termed **Stress Degree Day (SDD)**, the summation difference between canopy temperature of stressed and non-stressed plants, called **Temperature Stress Day (TSD)**, the **Temperature-Time Threshold (TTT)** which calculates the amount of time that canopy temperature is higher than a temperature threshold indicating stress, and the **Crop Water Stress Index (CWSI)**, which quantifies the level of CWS comparing its canopy temperature with that of a non-water-stressed crop and a maximum stressed crop, normalizing it with the ambient air temperature at a given vapor pressure deficit. Among them, the most used index in field crops is the CWSI. Finally, selecting the most representative leaf (or angle for the canopy) as an essential prerequisite in temperature-based methods is essential for using these thermal indexes. Also, measures must be made under stable conditions that exclude as many potentially influencing factors as possible, including the time of day and angle of view of the instrument.

### 3.2.2 Effects on crop phenology

In field crops, water requirement is generally low at early growth stages, maximum at reproductive growth stages, and again lower during terminal growth stages. Cereals are more sensitive to water deficit at or just before **anthesis** (Christen et al., 1995). At the beginning of the crop cycle, during **seeding**, the embryo within a seed is dormant and highly tolerant to desiccation, but it loses its tolerance upon germination and emergence (Blum, 1997). Song et al. (2019) found that severe water stress during the seeding stage greatly affected the growth and development of plants. However, most studies neglect the influence of water stress during the seeding stage on field crops. The mean documented effect of water stress on phenology is a **delay in crop development**.

Water stress generally retards the **leaf appearance** of field crops, but such an effect is not evident. Particularly, leaf initiation is very sensitive to water stress in some field crops (Kiniry et al., 1991), and the initiation rate can be halted if this stress is sufficiently severe. It has been shown that water stress **slows down** or stops the leaf-tip appearance of maize (Ge et al.,

2012), sorghum (Craufurd and Peacock, 1993), and wheat (Angus and Moncur, 1977). However, the leaf appearance of wheat was 10% faster with water stress treatment than with irrigation (Baker et al., 1986). Likewise, the leaf appearance of maize can show a short-term delay due to water stress, but the effect largely disappears with silking (Begonia et al., 1987).

Water stress can **delay** the onset of tasseling (male flowering) and silking (female flowering) in maize (Westgate, 1996). This can lead to **asynchronous flowering**, affecting pollination and potentially reducing kernel set. Particularly, stress during **pre-flowering** or early flowering can cause **inhibition of floral induction**, spikelet death, and zygotic abortion, leading to delayed or completely inhibited flowering. Combined water and heat stresses have also a significant effect on pollen germination (Bheemanahalli et al., 2022). However, mild stress can also cause **advanced flowering** (reducing the length of the vegetative period) in wheat, according to Angus and Moncur (1977). A water deficit during any stage of filling development causes the premature **cessation of grain filling**. The stage of meiosis is perhaps the most stress-sensitive period of reproduction in grain species. Indeed, kernel moisture content and its direct impact on metabolism appear to be key regulatory factors in shortening the duration of grain filling.

### 3.2.3 Effects on crop growth

Leaf growth is the main source of crops and is particularly high-sensitive to water stress. **Leaf expansion** may be limited or stopped by inhibited cell division, even by a slight reduction of water potential in the tissue (Hsiao and Xu, 2000). A generalized **morphological effect** of water stress on field crops is that leaves grow smaller and thinner than well-watered leaves (Vos and Haverkort, 2007). Water stress during vegetative growth could seriously affect the plant's structural components and, in a general way, reduces the growth of all the main parts of the plants. However, studies have shown that water stress can affect **the growth of plant organs** differently (e.g., Liu and Stützel, 2004).

Water stress will predominantly affect the **leaf size and the number of leaves** (Abid et al., 2016; Cakir, 2004) and may favor root growth over leaves (Hsiao and Xu, 2000; Parent et al., 2008). If water stress is severe, it can cause leaf folding and falling. This will reduce the total and the **effective leaf area** (the area capable of intercepting radiation), resulting in strongly reduced intercepted radiation and photosynthetic activity (Anjum et al., 2011), limiting at the same time the source size and the source capacity.

According to Moosavi (2012), water reductions in maize significantly affected morphological traits, including **stem diameter** and **leaf area index** reductions. Pettigrew (2004) also reported reduced overall plant stature with a 35% leaf area index reduction in cotton. Water stress occurring during vegetative and tasselling stages reduced plant height and leaf area development in a field study by Çakir (2004).

### 3.2.4 Effects on crop yield

The water stress directly impacts the source-sink relationship and can result in reduced **yield components**. Source-sink water stress refers to the situation where there is an imbalance between the water demands of the source (transpiration) and the water requirements of the sink (filling). Source-sink is sensitive to water stress depending on the phenological stage and the degree and duration of stress, and, in general, the sink will be affected if it experiences water stress or if the **source is reduced**.



Water stress applied during the **vegetative development** phase often does not directly affect the sink (e.g., in bean, Mouhouche et al., 1998; and maize, Cakir, 2004). However, some authors consider water supply during this phase essential, arguing that it favors deep rooting, one of the main resistance features to water stress. Also, the plant may prioritize water **allocation to the source** to maintain essential physiological functions, such as photosynthesis and transpiration, reducing water availability for the sink and leading to inadequate pollination and fruiting (grain filling in grain crops).

Water stress during the **reproductive period** will strongly affect sink reduction because it is when grain number and weight are determined (Ihsan et al., 2016; Saini and Westgate, 1999). During **pre-flowering**, about two weeks before reproductive organs' emergence, crops enter the period of yield determination (number of grains/kernels per spike/ear and the unit grain/kernel weight). In flowering, water stress can cause **pollen (male) sterility** and affect female **fertility** under extreme stress. It may also occur in relatively well-watered plants if reproductive structures are stressed. Water stress can also cause delayed silking, thus increasing the anthesis-to-silking interval, which is highly correlated with grain yield, specifically **ear and kernel number** per plant (Cattivelli et al., 2008). Modern maize genotypes tolerate up to 6 days of delay in silk emergence without pollination failure.

Water stress can also affect the **filling stage** (size and weight of grains). However, grain crops such as maize may tolerate mild water stress during the **late grain-filling stages** until maturity due to the low water demand during these stages (Song et al., 2019). Therefore, a high yield could be achieved through full irrigation at the flowering stage, even if the soil water content is sub-optimal during the grain-filling stages.

It is well known that even mild stress during a **reproductive period** can negatively impact **maize yield components**. Water stress at this stage can, for example, decrease yield by 3–4% per day, and this percentage can rise to 8% per day in case of severe water stress (De Araujo Rufino et al., 2018).

Abdelmula and Sabiel (2007) conducted a study on the effect of water stress at different growth stages of maize. They found that stress during the reproductive stage had the most significant negative impact on yield. In addition, Lizaso et al. (2003) stated that intercepted radiation by the source at the silking stage was a determining factor for maize grain number. That means the decrease in grain yield (sink) correlates with the decrease in maize leaf area (source), which water stress affects. These findings highlight that optimal leaf area is a crucial factor influencing grain number and overall yield in maize. Also, the final yield is directly affected by reducing the **number of plants** if water stress affects seedlings at the beginning of the season or if severe water stress causes plant failure.

### Box-c. C3 and C4 photosynthesis

Depending on the photosynthetic crop response to solar radiation (Figure 3.3), plants can be classified into two major groups with different modes of photosynthesis: **C3 and C4 crops**. They evolved in different climates; therefore, they need different environmental conditions for optimal growth. Generally, C4 crops are recognized as plants of warm and arid regions, while **C3 crops are of temperate origin**. Approximately 85% of the plants are C3, including rice, **wheat**, and **soybeans**. **C4 crops include maize, sugarcane, and sorghum**. Accordingly, **C4 crops are expected to adapt better to stress conditions than C3 crops** (Nayyar and Gupta, 2006). The main differences between C3 and C4 crops are:

- (i) **Biochemical features:** C3 and C4 crops differ in their primary carbon fixation pathways. C3 crops use the Calvin cycle to fix CO<sub>2</sub> into a three-carbon molecule, while C4 crops use the C4 pathway to fix CO<sub>2</sub> into a four-carbon molecule before it is released to the Calvin cycle. The C4 pathway involves several specialized enzymes and transporters that efficiently capture, concentrate and release CO<sub>2</sub> in the bundle sheath cells. This process requires more energy and resources than the Calvin cycle used by C3 crops. Thus, C4 crops have higher photosynthetic efficiency, especially in high light and high-temperature conditions, where they can fix CO<sub>2</sub> more rapidly than C3 crops.
- (ii) **Physiological features:** C3 and C4 crops differ in their response to environmental conditions, such as light intensity, temperature, and water availability. When stomata are open to let carbon dioxide in, they also let water vapor out, leaving C3 crops disadvantaged in drought and high-temperature environments. The C4 mechanisms help plants to reduce losses in hot, dry environments, but limit carbon dioxide entry to the leaf, leaving C3 crops at a disadvantage in low-light environments.

Thus, the complex anatomy and biochemical pathway of **C4 crops provide greater CO<sub>2</sub> fixation and photosynthesis efficiency**, enabling them to grow better in hot and dry conditions, meaning that they could benefit from the C4 energy-saving mechanisms. C3 crops have relatively low photosynthetic efficiency, and low CO<sub>2</sub> levels and high oxygen levels limit their photosynthesis. As a result, C3 crops tend to have lower yields in hot and dry conditions. While C3 photosynthesis has more room for improvement, it is possible to improve both types of photosynthesis to increase crop production.

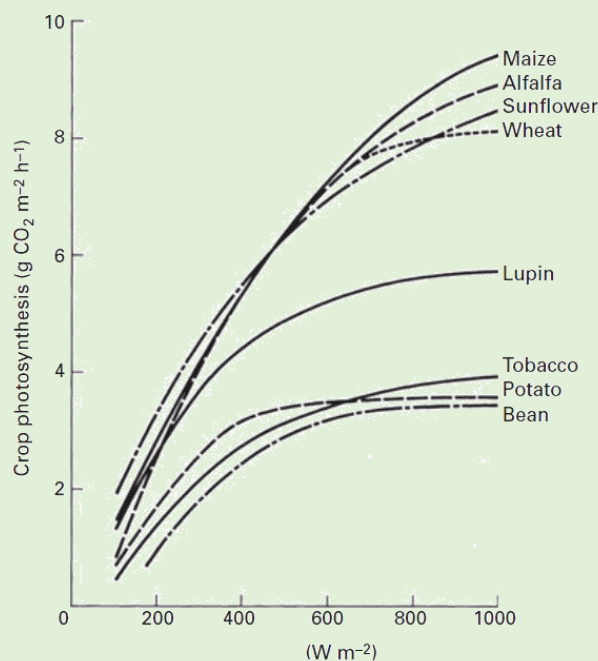


Figure 3.3. Photosynthetic crop response to solar radiation ( $W m^{-2}$ ) of different C3 and C4 field crops in field assimilation chambers (full-cover). Source (Connor et al., 2011a).



### 3.3 EFFECTS OF SHADE FROM AGRIVOLTAIC SYSTEMS ON CROP GROWTH AND DEVELOPMENT

#### 3.3.1 The importance of solar radiation for crops

Solar radiation is essential for crop production, providing extraterrestrial energy for crop growth and yield via the **photosynthesis** process, which may be defined as the intern biochemical process used by plants (generally by leaves) to convert carbon dioxide and water into glucose and oxygen. This process begins with the absorption of **light** (sunlight or others) by specialized organic molecules, called pigments, that are found in the chloroplasts of plant cells and finish with carbon assimilation. In addition to photosynthesis, radiation affects other important plant physiological processes, including **transpiration rate**, phototropism, photoperiodism, photomorphogenesis, pigment synthesis, and light-induced stress response. Light also affects **the assimilation of nutrients** and other plant functions. Day length and photoperiodism influence phenological events such as seed germination, flowering, and dormancy. Photomorphogenesis plays a role in shaping the structure and morphology of plants. Light-induced stress response refers to the capacity of plants to react to stress factors such as high temperature, water stress, and pathogens. It is also important to remember that the amount of radiation a plant receives also affects its temperature, which can also play a role in plant growth and development. Short days or shady environments also enhance thermotolerance and increase cold acclimation (Roeber et al., 2021). However, shade conditions can also improve water stress tolerance in plants.

Among all plant processes affected by light, photosynthesis is the most important for crop production since it is a direct cause–effect process linked to yield (Amanullah and Khalid, 2020; Muhie, 2022). Photosynthesis is characterized by the **Net Photosynthetic Assimilation Rate** ( $A_n$ ,  $\mu\text{mol m}^{-2} \text{s}^{-1}$ ). Thus, the faster the photosynthetic rate, the faster the plant grows, and the higher the photosynthetic rate, the higher biomass is created. However, not all solar radiation that enters the atmosphere is captured by plants, and not all the light reaching the leaf surface is used by photosynthesis. The total **radiation absorbed by crops** depends firstly on the amount of **incident solar radiation** (the energy per unit area received from the sun in the form of electromagnetic radiation), measured in watts per square meter ( $\text{MJ m}^{-2}$ ) and affected by a variety of factors such as local weather, the balance between direct and diffuse radiation, latitude, longitude, the day of year and daytime (Hafez et al., 2017; Yadav and Chandel, 2013). Then, it depends on the fraction of intercepted radiation by leaves, which depends on the leaf surface and other canopy characteristics (which will be more detailed in the next chapter).

The incident solar radiation is frequently integrated to determine the radiant energy received during a given period, called **Global Solar Radiation** ( $R_g$ ). The  $R_g$  variable on a surface is frequently expressed in  $\text{MJ m}^{-2} \text{day}^{-1}$  (for a daily integration). Plants can absorb only about half of the  $R_g$ . This portion is called **Photosynthetically Active Radiation** ( $PAR$ ).  $PAR$  includes the wavelengths that range from 400-700 nm of the electromagnetic light spectrum (Lambers et al., 2008; Percy et al., 2012). For photosynthesis-related processes,  $PAR$  is usually expressed in terms of light by the **Photosynthetic Photon Flux Density** ( $PPFD$ ,  $\text{mol m}^{-2} \text{s}^{-1}$ ). Thus, more intercepted and absorbed  $PAR$  generally equates to higher  $A$ . However, the photosynthetic rate also depends on the light quality intercepted by the leaves. However, as the light intensity increases, the photosynthetic rate eventually reaches a maximum point at which light intensity does not increase the photosynthesis rate, called the **Light Saturation Point** (LSP). The LSP is used in light environment optimization (Xin et al., 2019) to improve crop production.

The LSP is about 10% of full sunlight for shade-tolerant plants, 50-70% for C3 sun plants, and up to 200% for C4 sun plants (but each crop has its own LSP values for optimal growth and development). Finally, the quality of light refers to the portion of the electromagnetic spectrum available to drive photosynthesis in plants. According to Jin et al. (2023), blue light promotes vegetative growth, while red light promotes flowering and fruiting.

### 3.3.2 Shade stress concept

Although sunlight is required for photosynthesis, when extreme or unusual changes in the radiative environment of the crops occur (reduction, high intensity, or fluctuation), plants' mechanisms regulate photosynthesis to adapt to these conditions, affecting their production or stopping it. Usually, **radiative stress** is associated with high solar radiation, causing oxidative stress and resulting in photodamage and photoinhibition (Ganguly et al., 2018). The ultraviolet (UV) radiation may lead to severe damage to DNA (Hideg et al., 2013). Also, recurrent periods of high radiation followed by lower intensities (fluctuating radiation) may result in the prolongation of the light period (the photoperiod stress syndrome) (Nitschke et al., 2016). On the other hand, plants grown in shaded conditions can experience another kind of stress, as they may not receive enough energy to photosynthesize and grow properly (that will be called in this work "**shade stress**"). A plant experiences shade stress when it limits photosynthesis and affects the morphological development of the plant by affecting chlorophyll content, chloroplast ultrastructure, and photosynthetic processes (Fu et al., 2020). In agronomy, we can consider that a crop experiences shade stress when it affects the normal crop growth (vegetative, biomass), affecting (usually reducing) the potential yield. Shade stress may be characterized by the **shading rate** (the ratio between the reduction of the full-sun radiation and the total full-sun radiation) or by a ratio between the PPFD intensity and the LSP (with a physiological meaning).

Plants have a variety of responses to shade conditions, depending on their natural habitat and adaptations, affecting each crop differently. The short-term responses occur at the subcellular and cellular levels (Nicotra et al., 2010), while the long-term responses are related to the organ or whole-plant level (e.g., leaf thickness and biomass allocation). **Shade-intolerant crops** such as maize, wheat, sorghum, and soybeans require large amounts of sunlight for the best growth and to produce a high yield. On the other hand, **shade-tolerant crops** have developed mechanisms to maximize photosynthesis in partial or full shade conditions and benefit from shade during certain stages of growth, even increasing yield (Mathur et al., 2018). Some shade-tolerant crops include sugarcane, tea, lettuce, spinach, kale, and certain varieties of root vegetables such as beets and carrots. However, in shade-tolerant and intolerant crops, the effect of shade will depend on the level of shade applied (shading rate) and the duration and timing of shading.

### 3.3.3 Shading from AgriVoltaic systems

The **available** radiation to the crop in AV systems and its spatial distribution will be influenced by many parameters, that includes height, orientation, and density of the panels, the spacing of the panels' strips and their tilt or rotation axis, the type of solar panels (standard, bifacial, semi-transparent) among others. The majority of the developed AV projects use opaque PV panels (Ibrahim and Oum Kumari, 2020; Zainol Abidin et al., 2021), generating a **net and dynamic shade** over the crop, avoiding the pass of direct solar radiation, and then potentially inducing shade stress to crops. Therefore, it is necessary to find optimum arrangements of PV modules on the AV installations to define the optimal conditions for plant cultivation.

The **spatial and temporal** behavior of the available radiation can have important implications for crops grown in shaded environments, potentially benefitting or damaging them.

As a broad classification, AV systems can be divided into Fixed-tilt AV (FAV) and Dynamic-tilt AV (DAV) (e.g., the “HD” and “FD” FAV systems and the “ST” and “CT” DAV systems described in Elamri et al., 2018b and Valle et al., 2017). Both types create **spatial heterogeneities** of the radiation reaching the soil or the canopy, created by the “pore effect” of the PV panels blocking the direct pass of radiation beams. The shading rates (the percentage of reduced radiation compared to unshaded conditions) will vary depending on the density and orientation of the PV modules, the percentage of diffuse radiation each day, and the tracking strategy (in the case of the DAV systems). In this sense, the reduction of radiation under DAV systems will be more affected by panels’ density than by dynamic tracking, according to Amaducci et al. (2018). Weselek et al. (2019) also showed a seasonal dependence on shading behavior under DAV systems. Some shading rates reported in the literature for different AV systems are 30-50% (Dupraz et al., 2011), 13-30% (Amaducci et al., 2018), 40% (Majumdar and Pasqualetti, 2018), 30% (Weselek et al., 2019) and 30% (Trommsdorff et al., 2022).

However, it is possible to reduce the heterogeneities and shading rates for crop production purposes. A recent study (Perna, 2021) analyzing a range of FAV systems shows that it is possible to reduce the shadow duration **to increase the net daily available radiation** for crops and to **reduce the radiative spatial homogeneity** below the panels by varying the PV configurations (geometry, distribution, height, tilt and density of the PV panels), increasing the overall performance of these systems. Moreover, Tahir and Butt (2022) also assessed various strategies **to minimize shade-induced crop yield loss** under several FAV configurations, concluding that the best spatial homogeneity and the higher net daily radiation available for crops could be reached with PV panels facing East/West, while the traditional North/South faced fixed tilt PV panels result in higher spatial heterogeneity of the available radiation for the crop. Additionally, studies realized for greenhouse-FAV systems showed that a “checkerboard pattern” and the North/South orientation of panels improved the uniformity of light distribution and consequently diminished the PV shading effects on crops (Cossu et al., 2018; Kadowaki et al., 2012). Toledo and Scognamiglio (2021) examined different FAV technological and spatial design options to propose a systematic methodology to define the main attributes of these systems with the optic to increase their performance from a trans-disciplinary perspective.

However, compared to FAV systems, the DAV systems offers more flexibility and a degree of freedom **to optimize crop production** or other focused benefices (e.g., energy, water use) by reducing the spatiotemporal heterogeneities of available radiation for crops and by regulating the seasonal or “instantaneous” shading rates in the benefice of the crop (Valle et al., 2017; Wang and Sun, 2018). The technologies used in DAV systems may vary based on the techniques used to **control the movement of the PV panels** (rotation or rail movement systems), involving different advantages and disadvantages (Zainol Abidin et al., 2021). Among them, the most popular are those using **tracking systems** to rotate arrays of PV panels with respect to one or two axes. This DAV scheme permits, for example, the **control of tilt-rotation** angle to orient the face of panels toward the sun (called **Solar Tracking** – ST – strategy). Nonetheless, DAV systems also involve more complex optimization issues (involving more parameters compared to fixed systems).

Some industrials have developed tilt-controlled strategies using algorithms at the service of the plant by combining **crop radiative needs during the day or the season** with the electricity production objectives (optimized by an ST-based strategy). The inclusion of water use reduction or economic targets may also extend it. For example, an ST strategy (around 35% of shading rate) was compared to a called Controlled-Tracking (CT) strategy (around 20% of shading rate) designed to shade the crops during the hot hours, between 9 and 14 h UTC with the aim of **prevent water stress** (Elamri et al., 2018b). The ST plot has proven to be the most successful method for optimizing AV outputs, primarily due to electricity generation, while the CT layout was the most efficient regarding agricultural production. In another study by (Imran et al., 2020), various DAV systems with different densities of PV arrays were studied, suggesting that the ST strategy best suits most crops for North/South oriented modules. In contrast, a strategy called Reverse Tracking (RT) is the most suitable for crops that require higher PAR at their light saturation point.

More recently, new technologies such as vertical bifacial PV panels, semi-transparent panels, and wavelength-selective PV systems have been implemented and analyzed to perform transmitted radiation to the crop. **Vertical bifacial PV panels** provide several advantages, including **less land coverage**, less interference with agricultural machinery and rains, natural resilience to PV soiling, faster cleaning, and cost savings owing to a possible lower elevation. Riaz et al. (2020) evaluated vertically tilted Est/West-faced bifacial panels concluding that the vertical farm produces essentially the same energy output and PAR compared to traditional farms if the PV array density is reduced to half (or lower) relative to the full density of ground-mounted PV farms. Nonetheless, according to Riaz et al. (2021), the combined PAR/energy yields for this arrangement may not always be superior to the traditional optimally titled North/South faced monofacial systems.

To minimize the effect of completely opaque PV panels, neutral semi-transparent, and tinted **semi-transparent PV panels** have been considered a good option for both electrical production and agronomical purposes. This is possible because semi-transparent PV panels **limit shading** by intercepting only a fraction of the incident solar radiation. This aspect allows a **better distribution of solar radiation** on the underlying area than conventional PV panels. It was measured that the energy yield ratio of the semi-transparent module was slightly higher than those of conventional PV panels because of their capability of using ground-reflected radiation for energy production (Cossu et al., 2016). **Tinted semi-transparent PV panels** permit transmission to the crops of only a selected portion of the electromagnetic spectrum from the total amount of incident solar radiation arriving on the AV systems. For example, Thompson et al. (2020) showed that spinach and basil grown under tinted semi-transparent PV panels increased the proportion of red light reaching the plants, **improving the photosynthetic use efficiency** of light (up to 68% for spinach).

News opportunities are offered by **third-generation PV cells** based on semi-transparent organic PV cells (OPV) or dye-sensitized solar cells (DSSC). Technical analysis shows that OPV devices may struggle to perform better than opaque PV panels with partial coverage (Emmott et al., 2015; Meitzner et al., 2021; Ravishankar et al., 2021) and have the potential to produce a similar yield as under normal sunlight conditions (Liu et al., 2019). In turn, the variation in color and transparency are characteristics that can also be achieved by DSSC technology and represent a potential candidate to be considered as a **photo-selective covering for crops** (Kim et al., 2014; Roy et al., 2021). Intensive research on OPV greenhouses will certainly focus on

developing new optimized devices that minimize the impact on crop yield, improving the benefits of semi-transparent OPV or DSSC to achieve better crop yields in AV devices.

### 3.3.4 Effects on agrometeorological variables

Compared to an open environment, shaded environments induce complex changes in microclimate conditions. In particular, microclimate variations under PV arrays in AV systems influence plant yields depending on location within a solar array. These changes are specific to the situation (origin and nature of shade). Shade reduces solar radiation and thus directly impacts the energy balance in the soil–plant–atmosphere system. The “internal” microclimate below the AV systems is an integrated outcome of several-simultaneous **mass-energy transfer** processes, which include thermal exchanges of **convection** (ventilation) and latent heat (from evapotranspiration).

Several studies have shown the effects of AV systems on the main **agrometeorological variables** for different horticultural crops or perennial crops, concluding that microclimate variations under PV arrays influence plant yields depending on location within a solar array (e.g., Hudelson and Lieth, 2021). Specifically for field crops, which have dense canopies, it is expected that AV systems will affect the agrometeorological variables differently compared to horticultural or perennial crops, potentially influencing to a certain extent **air temperature**, **soil temperature**, relative humidity (or **vapor pressure deficit**), and **wind speed** and direction. The reduction of evapotranspiration rates and the general effects of shade on crops has been observed in other artificial, e.g., using protective **anti-hail nets or agricultural screens** (Mupambi et al., 2018; Solomakhin and Blanke, 2010; Tanny, 2013a), or naturally shaded conditions, e.g., in **agroforestry** (Kanzler et al., 2019; Karvatte et al., 2020; Monteith et al., 1991).

However, in the case of studies with artificial-partially shade, these are generally conducted with fixed shade or screens that may generate **different shading patterns** and rates compared to AV systems. In the case of **agroforestry** systems, the comparison with AV systems should be taken carefully since these systems also interact with crops through **competition for resources** and by influencing the microclimate through the transpiration of trees and other ecological processes. Thus, the study of the impacts of shade in AV systems requires an **independent analysis of the specific conditions** of the system involving the characteristics of the AV device, the size of the system, the strategy of shading, and the crop (tall crops will affect more the microclimatic conditions compared to small crops). The documented effects of shade on the main agrometeorological variables are presented below.

#### 3.3.4.1 Air temperature

Air temperature is an intuitive microclimate factor **directly influenced** by shade. Most studies performed on partial-shaded crops support the hypothesis that shading reduces air temperature compared to full-sun conditions (Möller and Assouline, 2007; Siqueira et al., 2012), but the degree can depend on different factors, such as the **height** of the structure covering the crop (Tanny et al., 2008) and the intensity and duration of shade (or the shading rate). For example, compared to full-sun conditions, measured air temperatures – near apple orchards' foliage – were **lower during the daytime** (about 1.4 °C) and **higher during the nighttime** (about 0.3 °C) (Tanny et al., 2009). Shade may also reduce temperature variation and maximum temperatures, as demonstrated for shaded agroforestry conditions (de Carvalho et al., 2021). Moreover, air temperature can vary vertically, associated with the vertical turbulent transport of air masses (Monteith and Unsworth, 2013).



For the conspecific case of AV systems, Barron-Gafford et al. (2019) documented a significant reduction of air temperatures under panels compared to full-sun conditions (around 1.2 °C during daytime). Also, they reported that the nighttime temperatures were around 0.5°C higher in the same AV system. Weselek et al. (2021) measured **significantly lower daily mean air temperature** compared to full-sun conditions by about 1 °C on average and throughout the year but most prevalent during summertime. Nevertheless, they also concluded that air temperature reductions under AV systems are **irregular during the year**. Similar results were reported by Al-Agele et al. (2021), who also measured significant differences between AV and full-sun mean air temperatures. In contrast, Marrou et al. (2013a,b) found **no significant changes** in daily mean temperatures and **thermal time** between AV systems and full-sun plots, measuring only slight reductions under shade (in Mediterranean conditions).

In general terms, shading has the potential for cooler air temperatures during the daytime and warmer temperatures during the nighttime. These changes may be non-significant for specific conditions or higher during the **hottest periods of the day**. However, this generic hypothesis may not always be true since several other factors play a role. For example, an increase in air temperature and humidity may occur if ventilation is reduced and if heat removal is impaired from the canopy (Tanny, 2013). The potential impacts on air temperature may also change through **shading rate** and **type of crop**. Finally, it is necessary to consider the case of regions with high solar radiation or the case of future **climate change** scenarios, in which the reduced air temperatures may be more significant.

#### 3.3.4.2 Soil temperature

Soil temperature directly affects plant growth, firstly because it is a major factor that drives the germination of seeds. In particular, surface soil temperature tends to be **lower than air temperature** but can fluctuate more rapidly. This is primarily because the soil receives less direct solar radiation than the atmosphere. The **fluctuations** occur mainly during the daytime when the soil surface absorbs radiation and heats up. However, it loses heat relatively quickly through conduction and convection with the cooler soil layers and the surrounding air. Daily fluctuations can be more influenced by **evaporative demand** and **soil water content**.

Shading can impact soil temperature directly **by reducing incoming radiative energy** but also **by reducing latent heat energy losses**. Thus, the general hypothesis is that increasing shading from panels corresponded with decreasing soil temperature.

It has been demonstrated that shading can reduce the soil temperature by cover screens (e.g. Tanny et al., 2009; Waggoner et al., 1959). Shading can reduce soil temperatures at midday up to 1.5 °C during the day compared to full-sun, reaching 2.5°C on hot days (Aguiar et al., 2019). In shading agroforestry conditions, Ehret et al. (2015) found that mean soil temperature at 5 cm depth was significantly affected by severe shade, approximately 1 °C lower than in full-sun plots for two years. In contrast, in moderate shade this reduction was 0.5 to 0.9 °C, also commenting that the differences among the shade levels only occurred in the second half of the growing season. Also, de Carvalho et al. (2021) indicate that the mean daily soil temperature (at 10 cm depth) of agroforestry coffee systems was lower (from 0 to 2 °C) under shaded conditions compared to full-sun plots.

In **AV systems**, the studies also support the hypothesis that soil temperature is significantly reduced under shade. Imran et al. (2020) stated that the (modeled) soil temperature in AV systems is **systematically reduced** compared to full-sun conditions, regardless of the shading

strategy. Marrou et al. (2013a,b) measured significant reductions in soil temperature for two crops, ranging from 1.9 °C in non-irrigated wheat and 0.5 °C in irrigated lettuce to 2.3 °C at 25 cm and 5 cm depth, respectively. Further, Weselek et al. (2021) indicated that the soil under PV panels is **heating up more slowly** and less strongly compared to full-sun conditions, measuring lower mean daily soil temperature under AV by 1.2 °C and 1.4 °C, on almost every day from the beginning of March to the middle of October in 2017 and 2018, respectively. Meanwhile, Al-Agele et al. (2021) measured **lower mean soil temperature**, 20 °C in the panel area, against 25.6 °C in the full-sun area.

However, using other kinds of PV panels may lead to **higher soil temperatures**. For example, higher daytime soil temperatures (from 0.8 to 2.8 °C) were measured during a typical summer day under **organic semi-transparent** PV panels (Friman-Peretz et al., 2020).

#### 3.3.4.3 Wind speed

Wind influences crop production in two ways: through physiological and mechanical impacts. Among the impacts of speed wind on crops, we can list the potentially increasing **supply of carbon dioxide** to the plants, which may result in higher photosynthesis and **transpiration rates** (Tanny, 2013). The mechanical impacts can primarily **damage leaves and shoots**. The major effects that could be induced by PV panels in AV systems are (i) the increase of the **resistance to airflow** and the **air exchange rate**, which can decrease the mean air velocity under the panels and modify the evapotranspiration and thermal properties, and (ii) the reduction of the wind speed, **protecting plants** from wind damage and creating a more stable **microclimate**.

For crops covered by screenhouses, Tanny et al. (2003) showed that the **air exchange rate was lower** than in full-sun conditions and that this depends on the **external wind speed**. More recently, Teitel and Wenger (2012) suggested that the **structural properties** of cover screens (area and shape) may also affect ventilation below them. **Significant differences** in mean **wind speed** were found under AV systems by Adeg et al. (2018) and Al-Agele et al. (2021). However, the analysis of the resistance to airflow and the vertical air masses exchange may be complex in AV systems. It may require modeling studies, particularly in systems with vertical PV panels or dynamic rotation.

#### 3.3.4.4 Vapor pressure deficit

The **Vapor Pressure Deficit** (VPD) is usually more agronomically used than relative humidity, as it refers to the difference between the water vapor content in the air and the water vapor saturation point of the air, signaling the **degree of “dryness”** in the microclimate of crops. Plants respond to changes in VPD through **leaf-atmosphere water exchanges** regulated by stomatal behavior, which can consequently affect transpiration, photosynthesis, and leaf-level water use efficiencies. The higher the VPD, the more the plant can give off water through transpiration. It does not cause a problem for short periods since the plant will rapidly recover by absorbing water from the dynamic surrounding air. When the VPD stays high for a more extended period, the plant may be unable to recover, and irreversible plant damage. In extreme cases, burned leaves can occur.

The VPD cannot be impacted in shaded conditions directly since it is a variable **independent of solar radiation**. However, the reduced air and crop temperatures generally lead to increased transpiration, which will influence the water vapor content in the air. Also, in the specific case of shaded conditions by PV panels, **air exchanges** may be reduced, reducing the

removal of water vapor from the crop environment. When there is no air movement, the air around the leaves will become **saturated** with water vapor, slowing down the process of evaporation. Studies show that VPD may be **reduced during daytime** under shading conditions (Möller and Assouline, 2007). It is related to a decrease in temperature, even if the absolute humidity is nearly unchanged (Tanny et al., 2009). Also, the VPD near the plants may vary within the canopy in unexplored ways. Thus, like wind speed, the effects of shade on VPD (and their effects on crops) should be analyzed by detailed experiments or modeling approaches.

### 3.3.5 Effects on the water budget

The influence of shade on the water budget of crops has been well-documented in the literature. Shading in microclimate conditions generally leads to a **reduction in crop water use**. This reduction is attributed to decreased radiation, resulting in cooler daytime temperatures and warmer nighttime temperatures. As a result, plants can **reduce transpiration** compared to crops grown under full-sun conditions. Additionally, shade helps conserve **soil water moisture**, thereby **reducing irrigation** needs. These combined effects can increase **water productivity** in AV systems, particularly in **dryland environments**. For example, studies by Barron-Gafford et al. (2019) demonstrated increased water productivity of jalapenos (*Capsicum annum*) (157% greater) and tomatoes (*Solanum lycopersicum*) (65% greater) in shaded AV systems compared to full-sun conditions. Additionally, PV panels can capture and store rainwater in AV systems (Dinesh and Pearce, 2016). This water may be used to supply **irrigation during the dry season**, contributing also to improving the **water use efficiency** of the system (Punde et al., 2022). The amount of harvested water will depend on the geometry and size of the PV panels (Şevik and Aktaş, 2021).

#### 3.3.5.1 Soil water content

Shade directly affects soil water content. Recent research conducted in shaded AV systems by Adeh et al. (2018) found that the soil surface under PV panels exhibited significantly improved **water conservation**, 328% more efficient than in full-sun conditions. They also showed that **rates of soil water depletion** varied with the shading treatments, leading to significant differences in the late season. Also, PV panels introduce local **spatial heterogeneity in soil water** conditions throughout the growing season, resulting in water concentration in specific field areas. This effect is mainly due to the effects of PV panels on **rainfall redistribution**, concentrating water on the soil-projected edge zones of the PV panels. It may be minimized by effectively managing shade patterns (Elamri et al., 2018a) based on rainfall intensity, wind speed, and wind direction.

#### 3.3.5.2 Evapotranspiration

The influence of shading on evapotranspiration is the most obvious impact of shade on the water balance of crops. Evapotranspiration is a key parameter in the atmosphere, plant, and soil **water exchanges**. Soil evaporation and plant transpiration relate to water demand for crop production by four variables: (i) the **climatic demand**; (ii) the proportion of **ground covered** by plants; (iii) the plant **stomatal conductance**; (iv) the bare **soil hydraulic conductance** (Mekonnen and Hoekstra, 2011).

Shading will directly affect evapotranspiration rates by reducing the incoming energy available for evaporation and transpiration processes in the soil-plant-atmosphere system (Bousselot et al., 2017). **Global radiation** represents the **total energy** input available for evapotranspiration (Allen et al., 1998), including the diffuse and direct fractions. **Direct**



**radiation** provides the **most energy** to drive evaporation and transpiration. In **shaded conditions**, only **diffuse radiation** is available for evapotranspiration, which is much lower in intensity than direct radiation, which explains the reduced evapotranspiration rates in shaded systems. However, under **high direct radiation**, evapotranspiration rates can also be reduced indirectly by the effects on leaf responses (which may close stomata to **limit water losses**).

Some studies estimate evapotranspiration in crop-shaded systems, mainly in **agroforestry systems**. In general, shade in agroforestry systems has significantly **reduced evapotranspiration** (e.g., Lin, 2010; Raz-Yaseef et al., 2010). However, as mentioned before, evapotranspiration in shaded agroforestry conditions should differ from that in artificial shading conditions, mainly because of the canopies' interactions and the competition issues. In the case of studies with protected crops by **shade screens**, Möller and Assouline (2007) reported **evapotranspiration reductions** of up to 38% compared to full-sun plots. In greenhouse crops, Lorenzo et al. (2003) found that total evapotranspiration was 32% lower in **shaded greenhouses** compared to control conditions.

More recent studies focusing on **AV systems** have also reported reductions in evapotranspiration, ranging roughly from **10% to 30%**, depending on the level of shading (Adeh et al., 2018; Marrou et al., 2013c; Weselek et al., 2021). These studies have also revealed that shading affects evapotranspiration more significantly during spring than in summer. Elamri et al. (2018b) conducted **modeling** research for the **water budget** in lettuce (*Lactuca sativa*) under AV conditions, reporting similar evapotranspiration reductions (reaching up to 33% compared to the full-sun conditions). Jahanfar et al. (2016) used **lysimeters** to measure evapotranspiration in shaded and unshaded areas of a photovoltaic green rooftop system, showing evapotranspiration of 38% lower in the unshaded conditions during summer-irrigated periods. Another study by Jiang et al. (2022) **separated soil evaporation and plant transpiration** measurements at different shading rates, observing reductions from 10% to 26% in transpiration and 21% to 41% in soil evaporation for the AV systems. However, shade patterns in AV systems may vastly differ in space and time, which may impact the evapotranspiration rates differently. Therefore, a correct assessment of the diurnal and seasonal shading variations must be considered in evapotranspiration estimations in AV systems.

### 3.3.6 Effects of shade on crop temperature and crop stress

Crop stress and plant growth is typically linked to air temperature in most agronomical studies. However, crop temperature (leaf, canopy, flower, or shoot apex temperature) and air temperature are unequal. While air temperature is only a measure of the motion energy of the gases that make up air, affected mainly by other weather parameters, **crop temperature** considers the interplay among plant traits, plant water availability, and microclimate around the crop (Michaletz et al., 2016). Indeed, crop temperature, and not air temperature, is the direct key variable that affects plants during growth and allows more accurate estimations of the effects of heat stress on crop yield (Gabaldón-Leal et al., 2016; Siebert et al., 2014). Leaf temperatures under the sun can be 10 °C higher than air temperatures during the day, depending on plant species, water status, and leaf location. Under shade conditions, temperatures may drop a few degrees below air temperature (Vogel, 2009).

Environmental factors associated with **energy balance** (notably, solar radiation and water) influence crop temperature and, eventually, crop comfort: the increase in radiant energy

absorbed by the leaves increases crop temperature. In contrast, liberating sensible and latent heat energy from the leaves to the air helps plants decrease crop temperature. Also, most plant processes (e.g., photosynthesis or respiration) will **speed up at higher crop temperatures**, positively or negatively affecting yield. For example, the rate of photosynthesis increases as the temperature rises, promoting faster growth and fruit production (Luan and Vico, 2021). Extreme high daytime temperatures can adversely affect growth and yields by causing **pollen sterility** and **blossom drop** (Hatfield and Prueger, 2015). A temperature rise also leads to **higher evapotranspiration** and reduced nitrogen use efficiency. Thus, shading will directly reduce energy bills, colling plants and preventing heat stress of crops, reproductive issues, and high-water losses (Kitta et al., 2010).

### 3.3.7 Effects on crop phenology

The plant mechanisms affected by shade and affecting phenology are partially understood. The main documented effect of shade on crop phenology is **delayed development** (similar that for water stress). Shade affects at the beginning of the season the crop development by reducing soil temperature, which may increase the **dormancy status of seeds** (Kigel et al., 1977; Orozco-Segovia et al., 1993), delaying emergence and influencing the timing of other crop stages (Stone et al., 1999).

During vegetative development, shade may directly influence the **Leaf Appearance Rate** (LAR). In wheat, it was shown that shade **speeded up LAR** during the first growth stages and until the start of milk development but prolonged the ripening stage (Arenas-Corraliza et al., 2021). In maize, a recent study shading maize during developmental stages showed decreased LAR with reduced radiation (dos Santos et al., 2022). They also showed that radiation was proportionally related to the total leaf number and that reduced radiation may delay **flowering initiation** (confirming similar results by Birch et al., 1998, who reported an increased duration of the "emergence to tassel initiation time" with increased photoperiod). Qin et al. (2022) also showed that shade **delayed flowering** and **reduced pollen** viability in alfalfa (C4 plant). Shading also led to a delay of tassel initiation, silking, and the end of flowering (11, 9, and 2 days, respectively) compared to full-sun conditions in maize (Schulz et al., 2018). However, they also reported that a slight shading rate (12%) did not cause a significant delay compared to the control. Flowering may also be delayed in C3 crops (wheat and mustard), as Singh and Alam (2020) showed.

### 3.3.8 Effects on crop growth

Shade affects the source of crops more complexly than water stress: shade reduces the size (**morphology** adaptations (Laub et al., 2022), reducing the source intensity (by reducing the energy to photosynthesis) but increasing the capacity (by optimizing the photosynthesis process (Fernández et al., 2004; Morgan and Smith, 1979). Often, this leads plants to allocate more mass in stems and less mass in their leaves, reducing **leaf thickness** and **total leaf area**, especially under high-shade levels (Artru et al., 2018b; Mu et al., 2010; Y. Wu et al., 2017b). However, low-shade conditions may increase the **total leaf area** (Dias-Filho, 2000).

In **soybean** (C3 crop), Wu et al., 2016 reported increased **specific leaf area** and **leaf area ratio** but decreased total leaf area under high-shade conditions (shading rate of 60%). In a recent study carried out under shaded AV conditions (Potenza et al., 2022), it was observed that shading rate (from 9% to 27%) **increased** crop **height**, **leaf area index** and specific leaf area, compared to full sun conditions. In **winter wheat**, low to moderate shade (shading rate of 8-23%) increased the leaf area index, mainly by increased area of the upper leaves (Li et al.,

2010). Also, Dufour et al. (2013) reported for wheat that the maximum leaf area index was not affected by shade when the latter absorbed less than 30% of incident radiation. In a C4 perennial grass, the leaf area index was not depressed by the reduction of incoming radiation, compensated by the increased photosynthesis efficiency of shaded plants (Cruz, 1997).

The **timing of applied shade** is also important when evaluating its impact on vegetative growth. For example, Artru et al. (2017) did not observe morphological adaptation in wheat as the shade treatment was applied after reaching the maximum leaf area index value. Shade may also reduce the **root/shoot dry matter ratio** in maize (Hébert et al., 2001; Page et al., 2011).

### 3.3.9 Effects on crop yield

Shade can significantly impact the source-sink relationships in field crops, hampering photosynthesis, causing a shift in carbohydrate allocation within the plant, limiting the assimilate supply to grains, and disrupting the hormonal and molecular signaling pathways involved in source-sink communication (Peet and Kramer, 1980; Trentacoste et al., 2022), leading (in most cases) to alterations of **yield components** and **reductions of final harvestable yield**. However, this effect will depend on the crop type, the cultivar, and the level and timing of shading. Most crops can tolerate low shading rates (around 15%), resulting in a **yield decline** that is **less than proportional** (Laub et al., 2022). However, shade-sensitive crops like forages, leafy vegetables, and tubers/root crops typically experience yield losses proportional to the shading rate. The spatial **radiative heterogeneity** in shading systems may also affect the spatial variation in crop yield, particularly in AV systems. Tahir and Butt (2022) showed that spatial variation in the **crop yield correlates** well with that of the net daily PAR spatial pattern in the case of the shade-sensitive crops (e.g., tomato), while the spatial yield for the shade-tolerant crops (e.g., lettuce) is less affected by this heterogeneity.

In general, **field crops** require large amounts of sunlight for growth and high yields, regardless of their metabolism (C3 or C4), and consequently, they are usually negatively affected by shade. Agroforestry studies have demonstrated that shade from trees can **reduce yield by significant margins**, e.g., up to 70% in sorghum, in a study conducted by Kessler (1992). The effect of shade on yield and yield components is particularly important when applied during **grain filling** (Andrade and Ferreiro, 1996). Also, there are probably an effect of shade on the **redistribution of dry matter** from vegetative organs to grains compensating the negative effects of shade, particularly **before anthesis** (Yang et al., 2021). However, this redistribution does not fully compensate for the reduced yield caused by shade compared to control conditions.

**C4 crops** like maize and sorghum experience significant yield losses even at low shade levels, with a disproportionately large decline in yield even with a 1% reduction in light availability, as reported by Laub et al. (2022). In the case of maize, studies by Cui et al. (2015) and Zhang et al. (2006) showed that shading significantly decreased maize yield, varying depending on the **duration and intensity of shading**. The **flowering-maturing stages** were identified as the most sensitive period, while the **seedling-joining** period was found to be the least sensitive. In the case of durum wheat (**C3 crop**), Dufour et al. (2013) observed that grain yield consistently decreased with (natural and artificial) shading, with high-shading rates (31%) resulting in a nearly 50% yield reduction. The **reduction in grain** yield primarily stemmed from decreased **grain number per spike** (up to 35%) and **grain weight** (up to 16%). However, they also observed increased **protein content** in shaded conditions (up to 38%). Consequently, the

protein yield per hectare was less reduced by shade than the dry matter grain yield. In contrast, under low-shade conditions (shading rate around 8%), Li et al. (2010) reported **increased grain yield** in wheat (up to 1.8%). More recently, in experiments conducted in Italy (Potenza et al., 2022) studying the effect of four different shading levels (from 9% to 27%) on the crop growth and development of soybean under AV conditions, the authors reported (on average) a reduction of yield and the number of pods per plant under shade (by 8% and 13%). They also reported a slight increase in grain yield (+4.4%) only in the area with a shading reducing 16% the radiation under full sun conditions. Currently, **improved varieties** with shade-acclimation traits may obtain **increased grain yield** in moderate to high shade. For example, improved wheat and barley varieties increased yield by up to 15%–20% with 25-50% shading rates in a recent study (Arenas-Corraliza et al., 2021).

### 3.4 SUMMARY

Water and radiation are two critical factors that significantly impact the **source-sink relationships** in field crops, with each factor exerting distinct morphological and physiological effects. It is important to note that the severity of shade and water stress and their **accumulation effect** in crops is closely associated with **the timing, intensity, and duration** of the stress. This will be limited by the **water and light requirement** and **sensibility** of water and shade stresses, which vary in crops and across the growth stages, from germination to maturity. Field crops may respond differently to short and long-duration water stress or/and shade during their different growth and developmental stages. From the consulted literature it is possible to formulate some assumptions.

**Moderate or severe** deficits in either water or radiation may induce **crop stress**, leading to delayed phenological development, restricted **appearance of new organs** (leaves, reproductive organs), and **decreased yield**. However, in the case of **slight deficits**, crops may experience certain benefits. Mild water deficit, for instance, can enhance **water productivity**, while low shade levels can improve **photosynthesis efficiency**. Both water stress and shade can lead to a reduction in the **number of plants** if they occur early in the growing season. Water stress, especially when severe, can cause **seedling desiccation**, while shade primarily induces **seed dormancy**, resulting in **delayed emergence**.

Throughout different growth stages, field crops exhibit specific patterns in their water and radiation requirements. During the **early growth stage**, water requirements are relatively high because this is the phase when field crops establish their root system and foliage. Then they may tolerate mild water stress during **stem elongation** and late leaf development. During the vegetative stages, water stress may decrease the source of crops by reducing the total number of leaves and the total leaf area, and if stress is severe, it can cause plant failure (directly reducing the yield). Field crops reach their maximum water dependence **during reproductive stages**, as it can lead to asynchronous flowering, disrupt pollination, and inhibit overall flowering. Then, water sensitivity gradually decreases during terminal growth, and crops may tolerate mild water stress during the grain-filling stages. However, severe water stress can result in premature cessation of grain filling.

On the other hand, **high radiative energy** is generally necessary for optimal growth and high yields in field crops, regardless of whether they follow C3 or C4 photosynthesis metabolism. However, C4 crops such as maize and sorghum are particularly sensitive to shade and can suffer significant yield losses even with low levels of shading. Despite this sensitivity to shade, certain crop stages of field crops may tolerate shade to some extent. Shade can help mitigate excessive heat and water loss throughout the vegetative period since the radiation will directly impact the source but not the sink and, if the shade is controlled, it may have a positive by increasing radiation use efficiency. Shading may influence **dry matter allocation** among different plant parts during stem-elongation and the late vegetative period, particularly affecting the root/shoot dry matter ratio. It may cause a delay in reproductive stages (but the impact on the sink may not be as strong). On the contrary, during **flowering initiation**, shade may protect crops from heat stress (which can inhibit flowering). However, shading during specific sensitive **reproductive stages**, such as fertilization, can disrupt pollination, resulting in **poor fecundation** and a lower grain set. Similarly, shading during grain filling hinders the plant's ability to convert carbohydrates into starch and accumulate dry matter, leading to smaller and less productive grains.

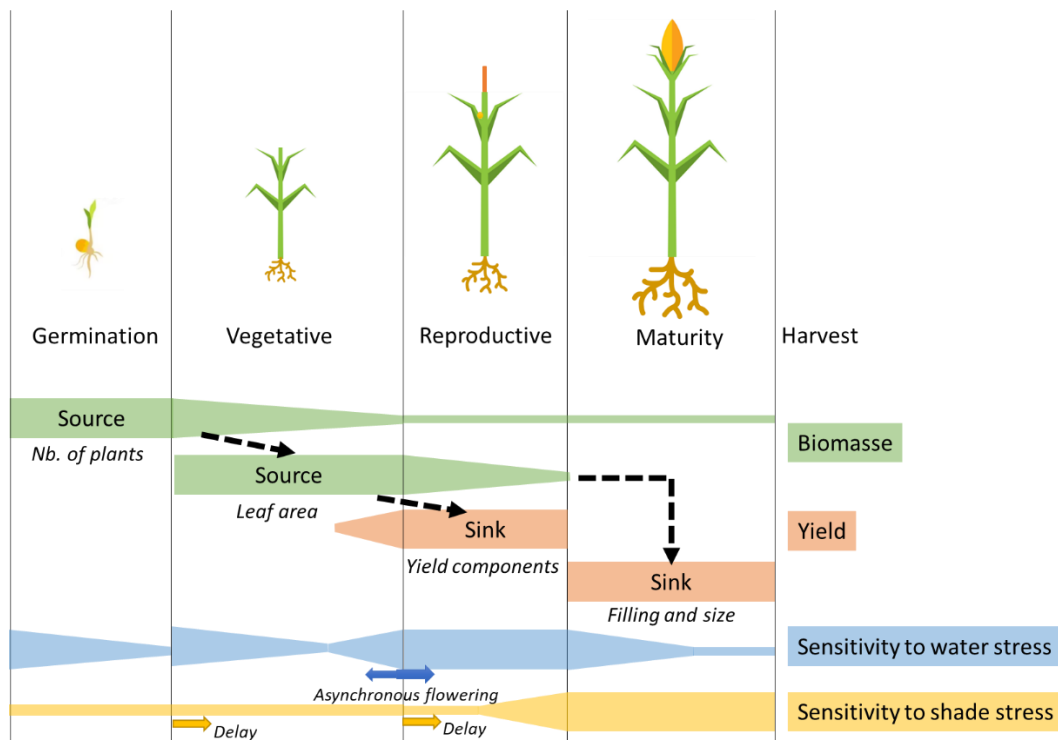


Figure 3.4. Sensitivity to water stress and shade of field crops' growth, development, and yield during the crop cycle.

Thus, we can conclude that both stresses will mainly impact the **source during vegetative development**, but the impact on the sink may not be as strong. **Reproductive stages are the most sensitive** to water stress and shade, as they can lead to asynchronous flowering, and any stress which **limits photosynthetic capacity** should be minimized. The **grain-filling stage is mainly impacted by shade**, and crops may tolerate mild water stress. **Severe water stress** is expected to have a **cut-off effect on yield**, causing failure of plants (mainly during early leaf development) or causing premature cessation of grain filling.

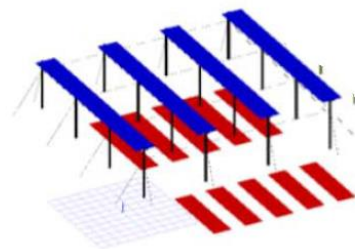
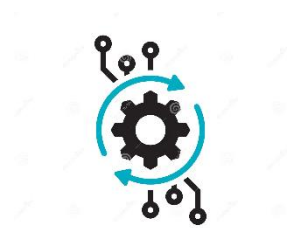
Under the most constrained conditions where stresses **occur simultaneously** or at **multiple growth stages**, the hypothesis is that yield will inevitably be reduced. However, the **cumulative effects and interactions** between water stress and shade in field crops have yet to be extensively studied. Particularly, the **positive effects of shade** on the water budget, such as improving soil water conservation and reducing climatic water demands, can **alleviate water stress**, especially in water-scarce or rainfed contexts. The influence of AV systems on the microclimate primarily involves **reduced climatic water needs** and slight **decreases in daytime air temperatures**. By implementing proper management practices, including precise **irrigation scheduling**, effective **shade management**, and appropriate crop selection, the challenges posed by shade and water deficiency can be mitigated, leading to optimized crop performance in such environments. Figure 3.4 shows a schematic resume of the sensitivity to water stress and shade of field crops during the crop cycle.



# CHAPTER 4

## MODELING SHADE AND WATER STRESS IN AGRIVOLTAIC SYSTEMS: THEORETICAL ANALYSIS FOR A GENERIC APPROACH

*"Nature is pleased with simplicity." — Isaac Newton*



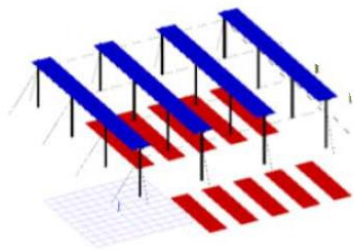




# CHAPTER 5

## EFFECTS OF SHADE AND DEFICIT IRRIGATION ON MAIZE GROWTH AND DEVELOPMENT UNDER AGRIVOLTAIC SYSTEMS

*“No experiment is ever a complete failure. It can always be used as a bad example.” — Jules Verne*





## CHAPTER 5 – EFFECTS OF SHADE AND DEFICIT IRRIGATION ON MAIZE GROWTH AND DEVELOPMENT UNDER AGRIVOLTAIC SYSTEMS

This chapter presents the results of the experimental works carried out to assess the combined and independent effects of shade and water stress on maize crop growth in fixed and dynamic AV systems, published in the *Agricultural Water Management* Revue (Volume 280, 30 April 2023, 108187). <https://doi.org/10.1016/j.agwat.2023.108187>.

### 5.1 MATERIALS AND METHODS

#### 5.1.1 Site description and environmental conditions

This study was conducted in the South of France (**Mediterranean climate**). Maize crop (*Zea Mays L.*, **RAGT IXABEL**) was grown for three years (2019, 2020 and 2021) in the agrivoltaic experimental platform of Lavalette (INRAE Montpellier, France: 43.6466 °N; 3.8715 °E), covering an area of 1720 m<sup>2</sup> (Figure 5.1). Sowing in the 2020 and 2021 seasons took place on April 2 and April 16, respectively, while in 2019 sowing took place on May 3. The length of the seasons was of 138, 144 and 152 days, for 2019, 2020 and 2021 respectively. Sowing and harvest were done on the same date for all treatments each season.

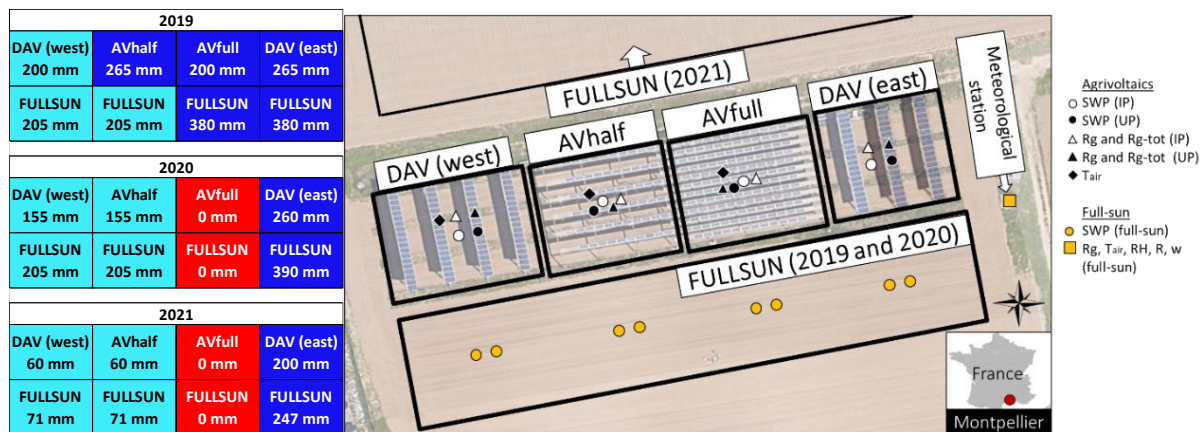


Figure 5.1. Experimental agrivoltaic site of Lavalette (Montpellier, France): maps of the experiments (left) and view from above (right). The map on the left depicts the location of the different plots during the three seasons, indicating the total amount of applied irrigation (in mm). The colors represent the different irrigation treatments: dark-blue for fully irrigated (FI), light-blue for deficit irrigated (DI), and red for not irrigated (NI). In the view from above, the symbols indicate the location of measurement devices: circles = Soil Water Potential (SWP) at 30-60-90-120 cm depths; triangles = Incident Global Radiation (Rg) and Total Global Radiation (Rg-tot); diamonds = Air Temperature ( $T_{air}$ ) and Relative Humidity of the air (RH). White-filled symbols indicate Inter-Panels position (IP) and black-filled symbols indicate Under-Panels positions (UP) in AV plots. Yellow-filled symbols indicate the sensors in FULLSUN conditions. The yellow-filled square indicates the position of the meteorological station, at the east of the plots, collecting multiple variables: Rg,  $T_{air}$ , RH and R in FULLSUN conditions. During the 2019 and 2020 seasons, the FULLSUN plots were located south of the AV platform. During the 2021 season, FULLSUN plots were located north of the AV platform, because of a germination issue in the conventional 2019-2020 FULLSUN plots. The FULLSUN plots in 2021 are not visible in the above view, but the instrumentation corresponds to that of the 2019 and 2020 FULLSUN plots.

The **environmental conditions** during the three cropping seasons were characterized by daily averaged values of five relevant meteorological variables measured in FULLSUN plot: **Air temperature** ( $T_{air}$ ), **Relative Humidity of the air** ( $RH$ ), **Incident Global Radiation** ( $R_g$ ), **Reference Evapotranspiration** ( $ET_o$ ) and **Rainfall** ( $R$ ) (Figure 5.2). The total amount of rainfall was modified in AV plots by using the methodology showed by Elamri et al. (2018a) to consider the effect of panels in rainfall interception. Daily air temperatures varied between 12 to 31 °C in 2019, between 10 to 28 °C in 2020 and between 9 to 27 °C in 2021. The 2019 and 2021 seasons were characterized by more overcast days (particularly in 2021), while 2020 was characterized by cloudy days observed at the beginning of the cropping season and mostly sunny days during the irrigation period. Rainfall during the cropping periods amounted to 150, 264 and 324 mm, in 2019, 2020 and 2021 respectively. This, coupled with the fact that rainfall events were mainly out of the irrigation period in 2019 and 2020, indicates that in 2021 experiments occurred in a rainy season, whereas in 2019 and 2020 during dry conditions.

Typical **cultural practices** have been adopted in a similar way during the three cropping seasons. Sufficient **nitrogen** amounts have been delivered to all plots (during sowing) to prevent nitrogen stress conditions.

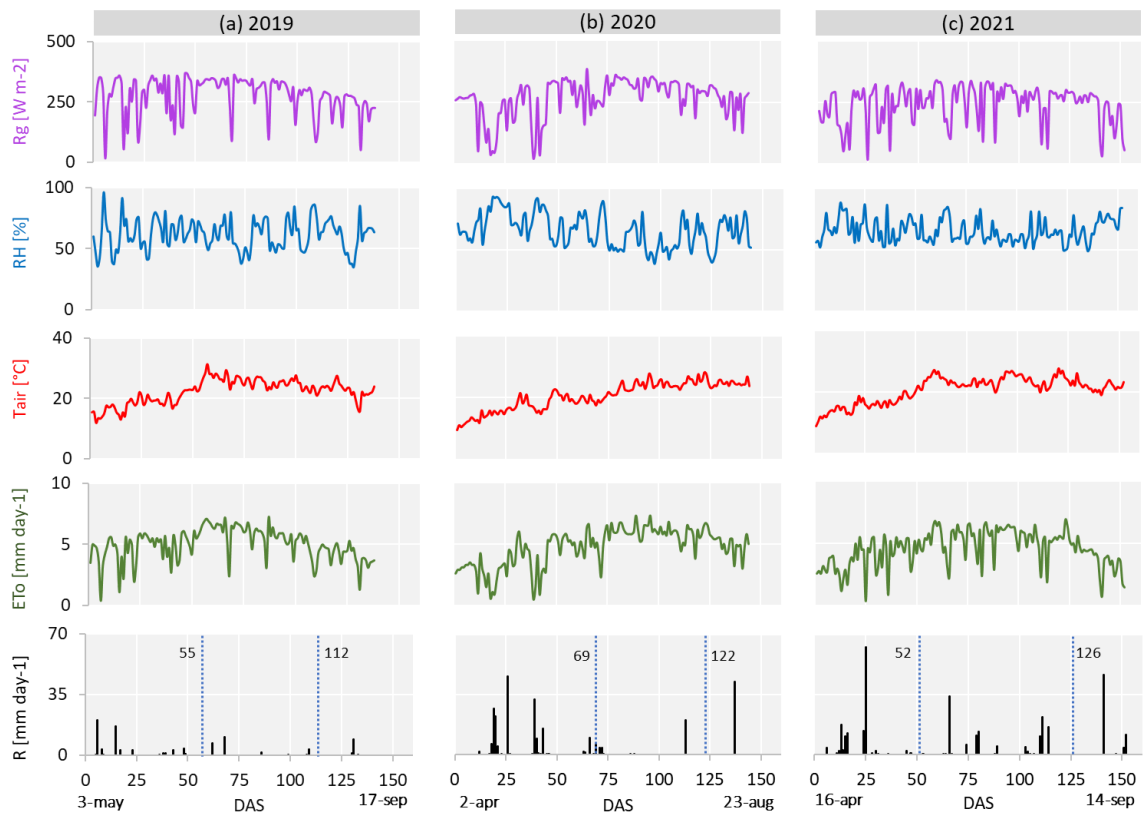
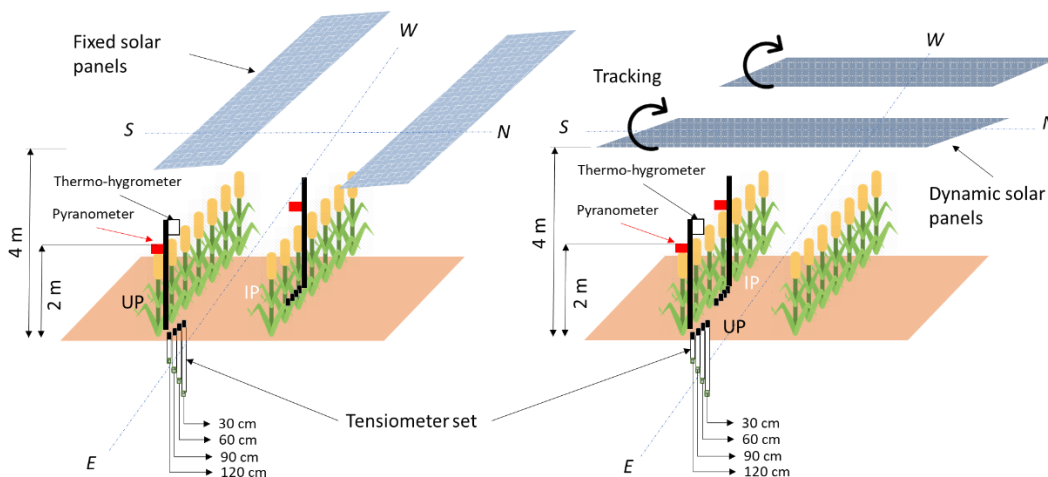


Figure 5.2. Daily mean values of the main meteorological variables measured during the three seasons (from sowing until harvest) by the meteorological station located at the east side of the FULLSUN plot: incident global solar radiation ( $R_g$  – yellow line); air relative humidity ( $RH$  – blue line); air temperature ( $T_{air}$  – dotted red line); reference evapotranspiration ( $ET_o$  – dotted green line); and rain ( $R$  – black vertical columns). The left vertical–logarithmic – axis corresponds to  $R_g$ ,  $RH$ ,  $T_{air}$  and  $ET_o$  and the right vertical axis corresponds to  $R$  columns.

### 5.1.2 AgriVoltaic devices and Irrigation treatments

The platform is composed of **four AgriVoltaic (AV) plots**, two fixed and two dynamic, with photovoltaic panels held at 4 m above the ground, resulting in different incoming radiation conditions for the crops. The two **fixed-tilt AV plots** “AVfull” and “AVhalf” (without tracker systems), consist of monocrystalline photovoltaic panels (1.58 x 0.81 m) installed with a fixed tilt angle of 25° with respect to the horizontal plane and aligned in strips of 22.4 m, oriented in the east-west direction. The “AVfull” plot corresponds to the full density of panels (as in optimal design for a solar energy production plant) producing a shading rate of approx. 50% (reduction of 50% of total global radiation available for the crop in the plot surface during a day). The “AVhalf” consists of the same design as the “AVfull” plot but with the half density of panels (one row of panels removed out of two) to limit radiation reduction, producing a shading rate of approx. 30%.

The two **1-axis dynamic AV plots**, called “DAV” (Dynamic AgriVoltaics) were added in 2014 on the eastern and western sides of the fixed subsystem, with 3 and 4 strips, respectively. Each strip in DAV consists of monocrystalline photovoltaic panels (1.98 x 1.00 m) aligned in 19 m long strips and oriented in the north-south direction. The strips are electrically controlled according to a horizontal axis rotation strategy called “**Solar Tracking**” thought to maximize radiation interception by the photovoltaic panels. This strategy consists of the panels’ faces following the course of the sun by varying the tilt angle of the strips between 50 °E and 50 °W. The resulting shading rate in DAV devices is about 35%, which is similar to the AVhalf structure, but with different subscale patterns regarding the drop shadows of the panels in space and time. The control plot without panels is called “FULLSUN” (representing a shading rate of 0%). It covers an area of 1760 m<sup>2</sup> and is located immediately south of the AV plots, without being affected by the shadow generated by the panels. More details about the AV platform of Lavalette were described by Elamri et al. (2018a,b).



*Figure 5.3. Scheme of the instrumentation to monitor radiation, air temperature and soil water potential in the fixed AV plots (on the left) and in dynamic AV plots (on the right). In the fixed AV plots (AVhalf and AVfull), the instrumentation was installed in different maize rows in a way to be placed in two different positions Inter-Panels (IP – between two arrays of solar panels) and Under-Panel (UP – at a vertical projected point below a solar panel). In the dynamic AV plots (DAV), the instrumentation was installed in the same maize row in a way to be placed in the two different positions IP and UP. The tracking control in DAV plots permits modification of the tilt angle from -50° to +50° in the E-W direction to follow the sun course during the day-time and in a horizontal position during night-time.*

Depending on the season, the shading conditions have been crossed with three different **irrigation treatments: Fully Irrigated Treatment (FI), Deficit Irrigated Treatment (DI), and Not Irrigated Treatment (NI)**. FI plots were irrigated when soil water potential dropped to -80 kPa (comfort limit for the silt-sandy soil texture of the site) based on **tensiometer readings** (Watermark probes, IRROMETER Company, Riverside, USA) at different depths, considering the dynamics of root water uptake and based on 30 cm readings between 60-80 days after sowing (DAS), on the mean of 30-60 cm between 80-100 DAS and mean of 30-60-90 cm from 100 DAS until the end of irrigations (around 120 DAS). DI plots were irrigated between -120 to -150 kPa soil water potential range to induce moderate water stress. The irrigation periods took place during DAS 55-112 (57 days), 69-122 (53 days) and 52-126 (74 days), in 2019, 2020 and 2021, respectively.

Water was applied using an **integral sprinkler system** in fixed amounts of 40 mm (to fill the soil water reserve of the first 30 cm and prevent water loss by deep percolation). In AV irrigated plots the amount was multiplied by 0.7 (amounts of 28 mm) in order to adapt to the approx. 30% radiation reduction in DAV and AVhalf. The pipes were installed each year before the irrigation period and removed before harvest. Irrigation applications to each treatment were measured with calibrated mechanical flow meters for each plot. Uniform water distribution among plots was ensured by a constant pressure water supply in a relatively flat topography, controlled with a variable speed drive booster pump and control pressure valves. Table 5-1 shows the experimental design matrix, indicating the level of combined stress and the variables studied for each cropping season.

Table 5-1. Experimental design table for the factors (shade and irrigation) and responses monitored, varying slightly between the three cropping seasons. The symbols in the stress column indicate the level of stress: ● = moderate shade (shading rate around 30-35%); ●● = high shade (shading rate around 50%); † = deficit irrigated (-120 kPa to -150 kPa); †† = not irrigated. The \* indicates that in 2020 only flowering was monitored (not leaf number). The letter after the shade factor indicates: D = Dynamic-tilt device and F = Fixed-tilt device.

Shade	Irrigation	Stress	2019	2020	2021
FULLSUN	FI	Control (no stress)	✓	✓	✓
FULLSUN	DI	†	✓	✓	✓
FULLSUN	NI	††		✓	✓
DAV	D FI	●	✓	✓	✓
DAV	D DI	●†	✓	✓	✓
DAV	D NI	●††			
AVhalf	F FI	●	✓		
AVhalf	F DI	●†		✓	✓
AVhalf	F NI	●††			
AVfull	F FI	●●	✓		
AVfull	F DI	●●†			
AVfull	F NI	●●††		✓	✓
<b>Crop growth and production (LAI, TDM and GY)</b>			✓	✓	✓
<b>Climate and soil water monitoring (R<sub>g</sub>, T<sub>air</sub>, SWP)</b>			✓	✓	✓
<b>Phenology (Leaf number and flowering)</b>				✓*	✓

### 5.1.3 Climate and soil water potential monitoring

**Microclimate data** were recorded with a **10-min** time step at a height of 2 m: a weather station was installed close to the FULLSUN plot: the **Air Temperature** ( $T_{air}$ ) and **Relative Humidity of the air** ( $RH$ ) by digital thermo-hygrometer (CS215, Campbell Sci. Inc.); Incident **Global Radiation** ( $R_g$ ) and **Total Global Radiation** ( $R_{g-tot}$ , that is a cumulated measure of  $R_g$  in a period) by pyranometer (SP1110 Campbell Sci. Inc.); **Rainfall** ( $R$ ) by pluviometer (52203, RM Young Company); and **Wind Speed** ( $w$ ) by an anemometer (05103-L, RM Young Company). Air temperature and global radiation measurements were also made in the AV plots. The thermo-hygrometers in the AV plots were installed in DAV (west) and AVfull plots for the 2019 cropping season and DAV (west) and AVhalf plots for the 2020 and 2021 cropping seasons. The thermo-hygrometers installed in AV plots were installed at a point covered by panels to differentiate from not covered sensors in the weather station installed for FULLSUN conditions. The pyranometers in AV plots were installed in two different locations, **Inter-Panels** (IP) and **Under-Panels** (UP), to capture the differences in the spatial intraday patterns of radiation transmission under the photovoltaic strips.

**Reference Evapotranspiration** ( $ET_0$ ) was calculated with the FAO#56 equation (Allen et al., 1998) using the recorded data of each plot at a daily timestep. Radiation in AV plots was the average of IP and UP sensors and rainfall amounts were corrected to consider the effect of the panels using the methodology showed by Elamri et al. (2018b). The other variables (relative humidity, air temperature and wind speed), less affected by the solar panels (Marrou et al., 2013c) due to the height of the structure above the crop, were assumed as the same for all treatments and taken from the FULLSUN weather station.

**Soil water status** was monitored by **Soil Water Potential** measurements ( $SWP$ ) using soil water potential sensors (Watermark) also recorded every 10-min at 4 depths (30-60-90-120 cm). Since solar panels are likely to cause large heterogeneity in soil moisture after rainfalls (Elamri et al., 2018b),  $SWP$  was also measured in two positions (IP and UP) for AV plots, similar to radiation measurements (see Figure 5.3).

### 5.1.4 Crop phenology, vegetative growth and production

**Plant emergence** was characterized by counting the number of visible plants that emerged in 12 rows per treatment, through a determined stripe of 13 m (covering an area of 123 m<sup>2</sup>). The emergence stage date was reported when the percentage of emerged plants reached at least 50%. The phenological development of the maize crop was monitored under the different water and radiative conditions by median dates of **vegetative stages** (leaf number) and **flowering stages** (tasselling and silking), which corresponded to the date when 50% of the plants reached the stage. The count in vegetative and flowering stages was carried out under each plot and for different rows, in 430 tagged maize plants, covering an average total area of 60 m<sup>2</sup> per plot. Leaf number monitoring was carried out only for the 2021 cropping season from V2 (2-leaf stage) until the first visible flowers appeared (n-leaf stage corresponding to the final number of leaves) by weekly counting of "deployed leaves", commonly the ligulate leaves for the maize crop (IOWA scale, commonly used in maize studies, as described by Abendroth et al. (2011)). The dates of the reproductive stages were identified in the 2020 and 2021 cropping seasons: tasseling (VT) and silking (R1), starting when at least one extruded anther or one extruded silk was visible in all tagged plants. All the phenology results are presented using plant age time (DAS), commonly used in agronomy.



During the three years of experiments the vegetative growth has been characterized by around 12 weekly measurements of **Leaf Area Index (LAI)**, using the LAI-2200C – LICOR system, from early vegetative development until observing a decrease in *LAI* (after the maximum *LAI* values), measuring ten values of *LAI* across a parallel central line between two central rows in each plot. **Crop production** has been estimated at harvest by a sampling of 40 tagged plants to estimate the **Total Dry Matter (TDM)** of aerial part only (leaves, stem, ears) and **Dry Grain Yield (GY)** for the three seasons, following standard methods: individual plants sampled without the root were separated into leaves, stem, and ears. The samples were then oven-dried at a constant temperature of 65 °C for 72 hours and weighed individually, separating the ears from the leaves and the shoots. Dry kernels were separated from the cob to estimate *GY*. **Harvest index** values (*HI*) have been calculated as the ratio of *GY* and aerial *TDM* at maturity (Kawano, 1990). Data on *TDM* and *GY* were subjected to analysis of variance (ANOVA) using R package (r-stats) version 2.0. The means were considered different if the *p*-value was less or equal to 0.05 ( $p \leq 0.05$ ). For all analyses, the normality and the independence of residuals and the intra-treatment variance equality were checked.

**Daily Growing Degree-Days (GDD, °Cd)** were calculated following the classical approach:  $GDD = (T_{mean} - T_{base})$ , where  $T_{mean}$  is the mean air temperature calculated as the daily average of 10-minute recorded data, and  $T_{base}$  is the base temperature, assumed 6 °C, as identified for this species in the south of France conditions (Brisson et al., 1992). Then we evaluated the relationships between *GDD* and leaf number, employing the **Phyllochron (PHY; °Cd leaf<sup>-1</sup>)** concept, also rendered as **leaf appearance<sup>-1</sup>** (dos Santos et al., 2022). The *PHY* is used to describe the growth and development of plants (especially cereals) by the relationship between leaf number and **Thermal Time** (*GDD* accumulation). We fit linear models to compute phyllochron values, where the slope of the line is the *PHY* for the entire leaf vegetative period. Model fit was assessed by R-squared. To provide an additional angle of analysis, we "extrapolated" this concept to analyze the radiation associated with the appearance of "one more leaf", by introducing the *PHY-r* (MJ leaf<sup>-1</sup>), computed as *PHY* but using "**radiative time**" (accumulated daily *Rg-tot*) instead of *GDD*.

### 5.1.5 Gas exchange measurements

Plant **gas exchanges** (stomatal conductance and photosynthesis) have been measured for different sunny days with clear sky conditions whenever possible during the 2021 season with a TARGAS-1 Portable Photosynthesis System (PP Systems), to identify the impacts of **Photosynthetic Active Radiation** variations (*PAR*) on **Stomatal Conductance** (*gs*) and the **Net Photosynthesis Assimilation Rate** (*A<sub>n</sub>*). The apparatus was mounted to pinch a leaf horizontally, taking care to avoid shadows from the plot or other plants. Measurements started early in the morning and ended in the afternoon.

## 5.2 RESULTS

### 5.2.1 Impact of the solar panels on agrometeorological variables

Figure 5.4 shows the total amounts of the **key agrometeorological variables** measured in the different shading conditions. We preferred to show thermal time instead air temperature because is a more relevant (empirical) driver of crop growth and is mostly used in maize studies. **Water inputs** consider rainfall and irrigation. In Figures 5.5 to 5.7, we focus our study on the reductions of radiation and air temperature measured under AV systems, which are the two expected and documented variables affected under shade that impact crop development in many ways. Relative humidity and wind were excluded from our analysis because of their marginal variations between the AV devices of Lavalette (Marrou et al., 2013a), and their secondary role in crop development.

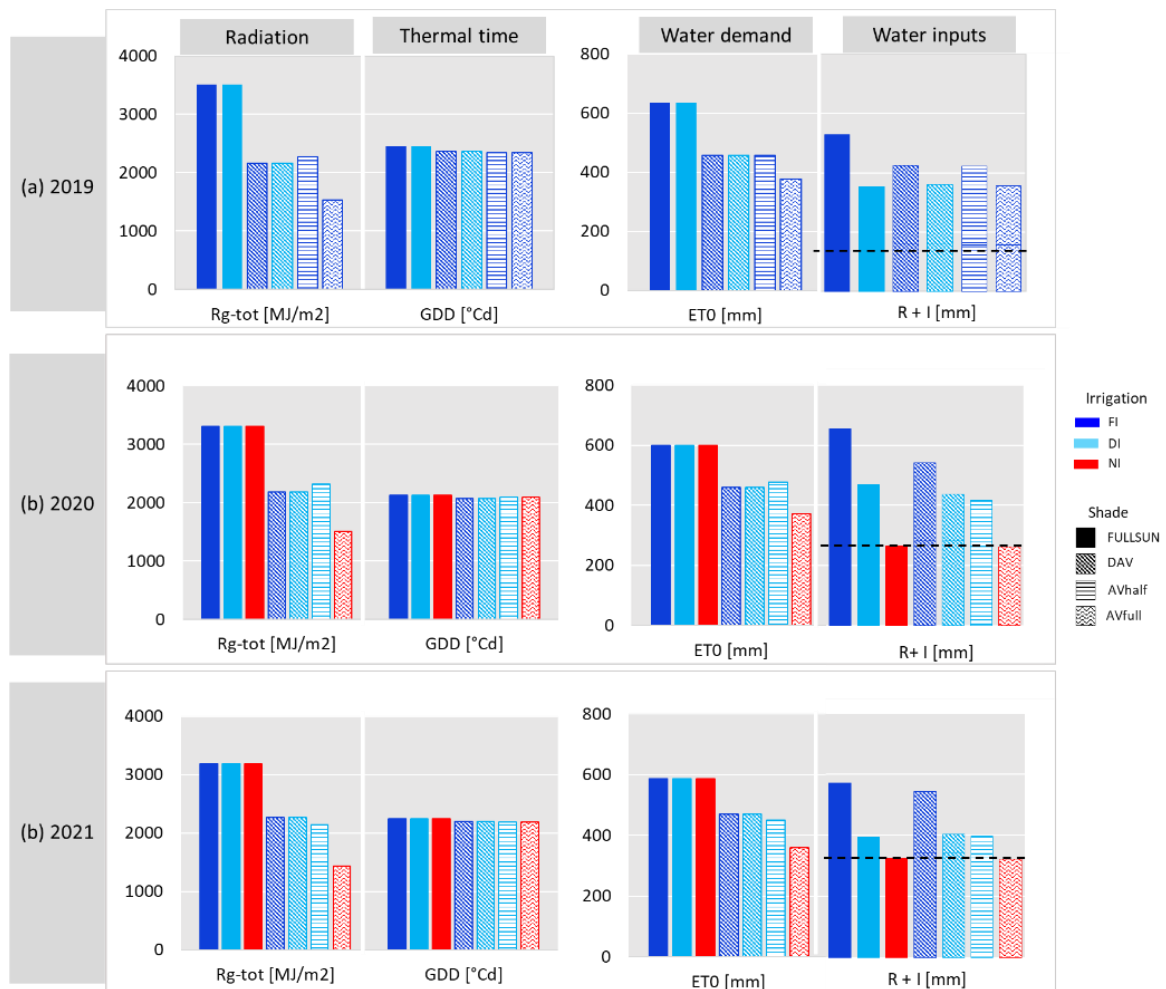


Figure 5.4. Cumulated key agrometeorological variables measured from sowing until harvest during the three cropping seasons (a) 2019, (b) 2020 and (c) 2021: Total Global Radiation ( $Rg\text{-tot}$ ) transmitted to the canopy (at 2m) in AV plots, computed as the average of the IP and UP sensors; Growing Degree Days (GDD); Reference Evapotranspiration ( $ET_0$ ), considered as the climatic demand of water and was computed by the Penman-Monteith method for each radiative condition; Rainfall (R) and Irrigation (I) inputs. The colors represent the different irrigation treatments: dark-blue for Fully Irrigated (FI), light-blue for Deficit Irrigated (DI), and red for Not Irrigated (NI). The rainfall amount is represented by the horizontal dotted line colored in black in the R+I columns. Shade treatments are differentiated by the fill patterns of the columns: FULLSUN plots are represented by solid-filled columns, DAV by diagonal-lines filled columns, AVhalf by horizontal-lines filled columns and AVfull by zigzag-lines filled columns.

In Figure 5.4, the **total solar radiation** measured under the panels in the different AV plots led to shading rates of **29-38% in DAV**, **30-35% in AVhalf** and **54-56% in AVfull**, depending on the season. These measured rates are consistent with those obtained previously in the same plots (Valle et al., 2017). The cumulated **thermal time** (cumulated *GDD*) did **not vary significantly** within the treatments, mainly because of the slight differences observed in air temperature (Figure 5.5). As expected, the **reference evapotranspiration** reductions in AV were **proportional to shading rates**. The analysis of total water input (rainfall plus irrigation) shows that fully irrigated plots reached in general the reference evapotranspiration (except for FULLSUN in 2019). In deficit irrigated plots, the **water inputs** were in general **lower than  $ET_0$** , by 21-44% in FULLSUN, by 6-23% in DAV and by 9-10% in AVhalf. In FULLSUN not irrigated plot water inputs were 51-53% lower than  $ET_0$ , however in AVfull, these values were only 6-17%. This is not surprising since radiation is the first driver of the  $ET_0$  equation. However, these results partly describe the effect of panels on the water budget, showing their impact on reduced reference evapotranspiration. The solar panels could affect the wind speed in each plot differently in a minimal way (see Marrou et al., 2013a), which represents a limitation on the usefulness of the calculated  $ET_0$  values. The study of the impacts of solar panels on the water budget will be delved into in section 5.2.2 thanks to soil water depletion analysis. A more detailed analysis based on the water budget (including actual evapotranspiration) was not included, given the uncertainties on different terms and due to spatial variability.

To analyze the intraday and daily dynamic patterns of incident radiation and air temperature, we focus on the 2019 cropping season because this year the monitored plots had more similar hydric conditions (reducing the risk of the influence of latent heat in air temperature measurements). Figure 5.4 shows that the **daily means of air temperature** were only slightly affected by the presence of panels for the three years of experiments, with temperature **reductions** under AV systems in the **range of 0 to -1.5 °C**. However, when considering hourly temperature means, obtained from values taken **each 10 minutes**, the **differences** between the AV plots and the FULLSUN plot were wider, ranging between **-5 and +3 °C**. In other words, higher differences only exist in the intraday air temperature values, with possible short-term effects on crop health. Air temperature reductions in AV plots occurred mainly during the nighttime and then around (the solar) midday (Figure 5.7a). On the other hand, air temperature augmentations in AV plots were observed in the afternoon (around 17:00), probably caused by air speed depletion around this time of the day. The slight reductions in daily air temperature registered in AV compared to FULLSUN also imply slight reductions in daily *GDD*: between 0.0 – 0.5 °Cd in DAV and between 0.0 – 1.2 °Cd in AVfull, resulting in a seasonal **reduction in thermal time of 89 and 110 °Cd**, respectively (Figure 5.7b).

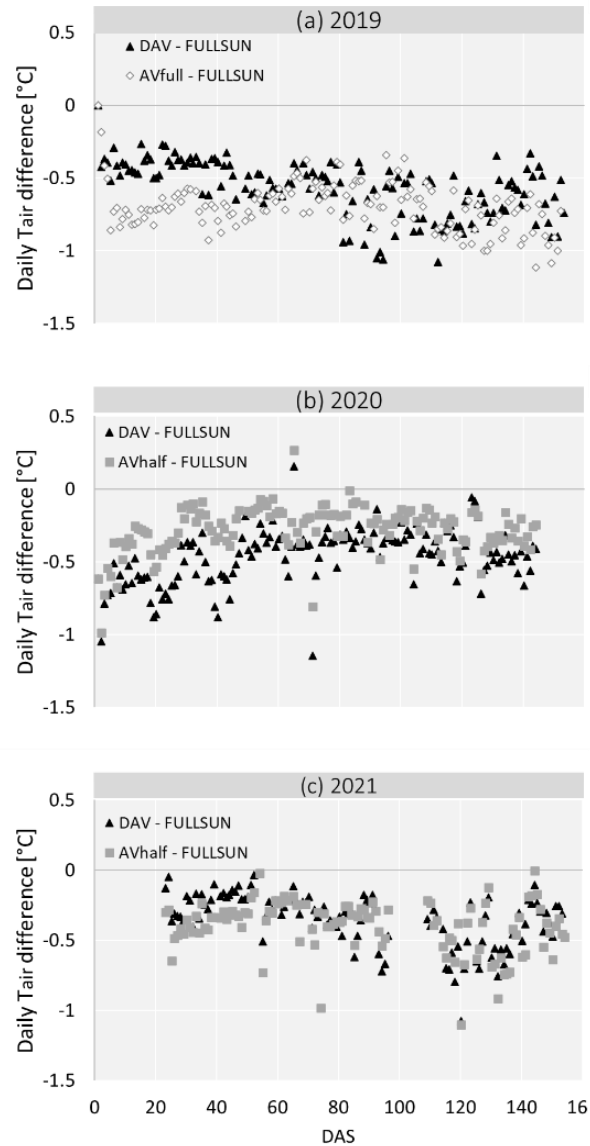


Figure 5.5. Differences in the daily means of air temperature ( $T_{air}$ ) between AV and FULLSUN plots for 2019 (a), 2020 (b) and 2021 (c). In 2019 the two monitored AV plots were DAV (west) and AVfull, while in 2020 and 2021 the two monitored AV plots were DAV (west) and AVhalf).

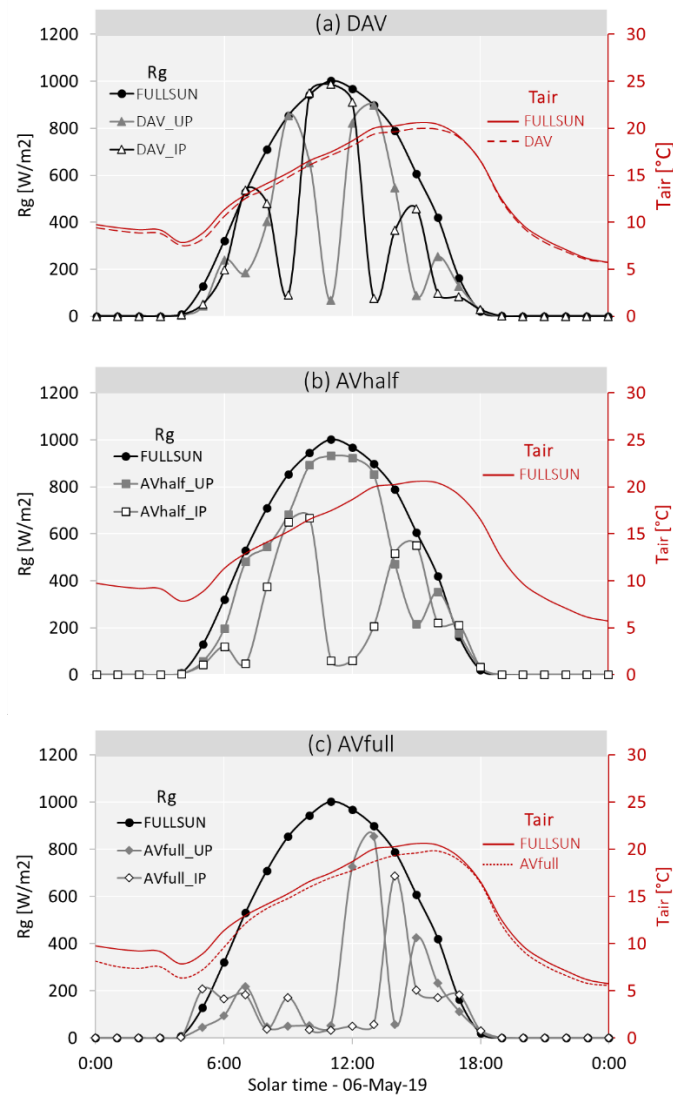


Figure 5.6. Hourly dynamics of the incident global radiation ( $R_g$ ) and air temperature for the DAV (a), AVhalf (b) and AVfull (c) devices, in comparison with FULLSUN conditions, showing differences between the IP (inter panel) and UP (Under-Panel) positions, for the sunny spring day of May 6th, 2019 ( $T_{air}$  was not measured in AVhalf for 2019). For legibility, the curves corresponding to air temperature data are in red, and the curves corresponding to radiation data are in black.

The spatial patterns of the available radiation under the AV plots of Lavalette have been modeled by Valle (2017) who showed more **homogeneous spatial distributions of cumulated radiation in dynamic AV devices** when compared to **fixed devices**. Confirmation is found in our experimental results: as an example, the daily cumulated radiation measured in DAV for the inter-panel (IP,  $19.2 \text{ MJ m}^{-2}$ ) and under-panel (UP,  $18.7 \text{ MJ m}^{-2}$ ) positions are very close on the sunny day of May 6, 2019 (Figure 5.6a). with  $19.18$  and  $18.71 \text{ MJ m}^{-2}$ , respectively. However, we observed that their hourly dynamics displayed a “mirror” behavior (curves in phase opposition), with magnitudes controlled by a bell-shaped curve in the course of any given sunny day in the FULLSUN conditions. The **temporal pattern was more irregular** in the **fixed AVhalf** (Figure 5.6b) and AVfull plots (Figure 5.6c) with far different cumulative **daily radiation** (Figure 5.7a) between IP and UP positions. This difference in cumulative radiation amounts also exists when considering **seasonal time scales** (Figure 5.7b). At the seasonal scale, the heterogeneity observed between the IP and UP positions for the AVhalf plot was

high: the (cumulated) radiation measured at IP was around 65% of the UP radiation, whereas the UP radiation was around 93% of the IP radiation for the DAV plots. In the AVfull plot, the difference between radiations in the IP and UP positions was smaller than in AVhalf (IP radiation was 83% of UP), probably due to the homogenous shade observed in both positions before midday (Figure 5.6c).

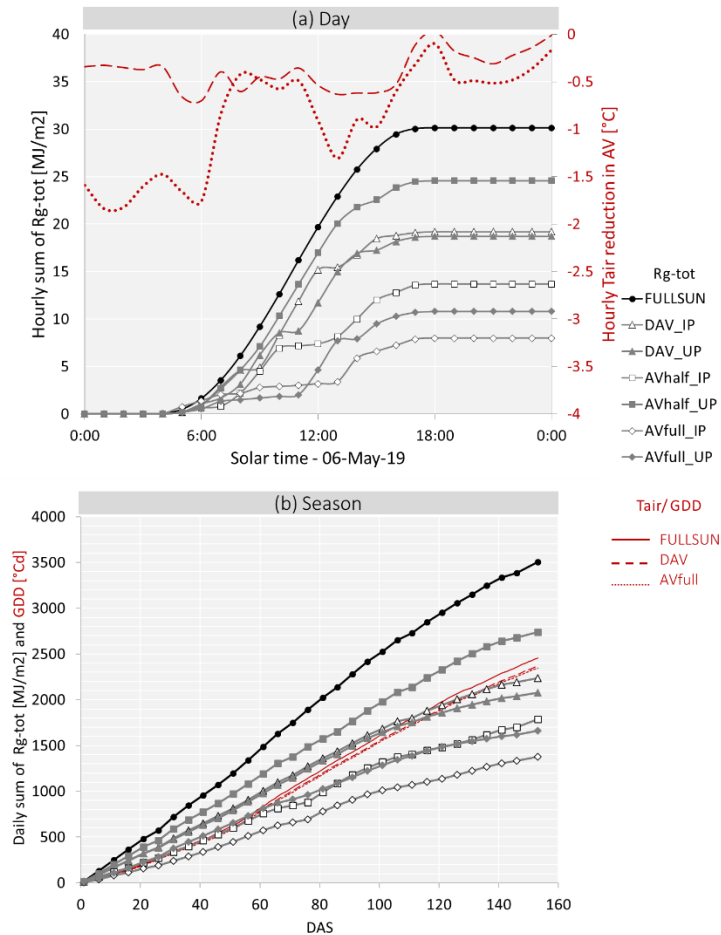


Figure 5.7. Cumulative total global radiation ( $R_{g\text{-tot}}$ ) for the FULLSUN, DAV, AVhalf and AVfull plots, also showing the difference between the IP and UP positions, and the hourly  $T_{air}$  reductions in AV compared to FULLSUN for the same spring day (a). Cumulative global radiation for the FULLSUN, DAV, AVhalf and AVfull plots, also shows the difference between the IP and UP positions and the values of growing degrees-days (GDD) for the whole 2019 season (b). For legibility, the curves corresponding to air temperature data are in red, and the curves corresponding to radiation data are in black.

### 5.2.2 Temporal dynamics of soil water potential

**Soil Water Potential (SWP)** is an indicator of soil water content, the evolution of which depends on evapotranspiration. As an illustration, we present the data collected during the season of 2020, where rain is less frequent. During that year, we also had the largest number of combinations of shading and irrigation levels (see Table 5-1). Figure 5.8 shows the **dynamics of SWP** observed from DAS 65 to DAS 145, covering the whole irrigation period, of the 2020 cropping season. For clarity, we chose to use the average between SWP values measured at 30, 60 and 90 cm depths, which we roughly considered as a proxy of the effort to be made by plant roots for water uptake from the soil. The first irrigation was applied on DAS 61, putting all irrigated plots (Figure 5.8a,b,d,e,g) in water comfort conditions at the start of the measurements. For the particular case of non-irrigated plots, SWP monitoring started later



(on DAS 85) showing moderate to severe water stress over the whole monitored period and slight **conservation of soil moisture** in AVfull (Figure 5.8c) compared to the FULLSUN conditions (Figure 5.8f), leading to a greener appearance of the plants in the AVfull plot.

The main general trends that we can draw from *SWP* dynamics are that (i) **soil drying was slower in the shaded plots** when compared to the FULLSUN plots, resulting in better soil water conservation and thus, reducing irrigation needs in AV and that (ii) soil drying dynamics and magnitudes were **different between the IP and UP positions under the fixed AV device** (AVhalf – Figure 5.8b) when compared to the dynamic AV device (DAV – Figure 5.8a,d), highlighting the advantage of using **tracking systems** to achieve a **more regular soil water content** in the plot surface. Going a bit more into detail, we observe that soil drying in the IP position of the AVhalf plot was slower when compared to the UP position (Figure 5.8b) as the UP position receives more radiation (Figure 5.8d), resulting in mild-moderate water stress in the UP position (*SWP* between -80 and -150 kPa) for most of the irrigation period, while soil water content was maintained high enough to hold *SWP* under the -80 kPa stress limit. A limitation of our results was the absence of rain redistribution and runoff water measurements during rainfall events.

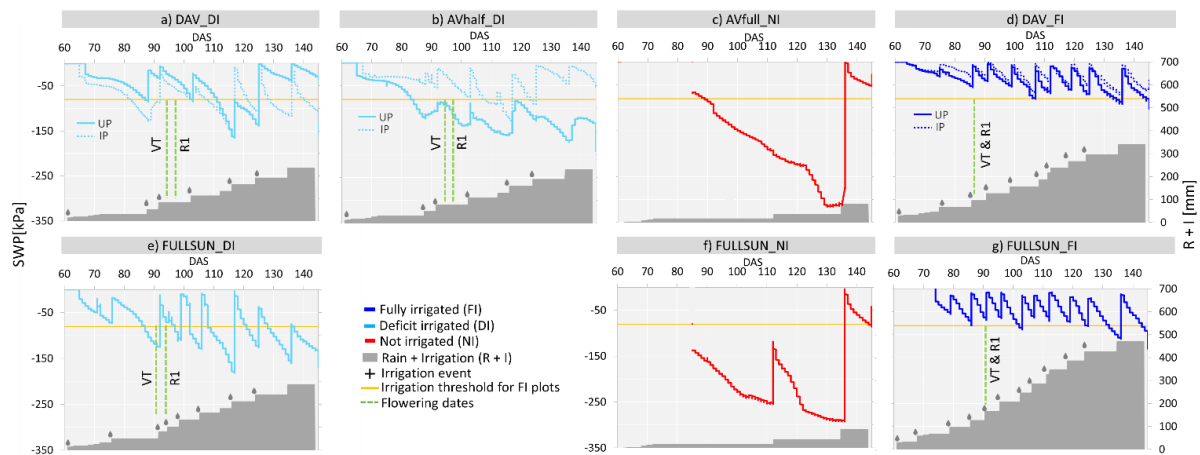


Figure 5.8. Dynamics of Soil Water Potential (*SWP*) and cumulative Rainfall and Irrigation amounts (*R + I*) for the different combinations of shading (FULLSUN, DAV, AVhalf and AVfull) and irrigation (FI – Fully Irrigated, DI – Deficit Irrigation, NI – Not Irrigated) conditions, for the 2020 cropping season. The *SWP* values shown are averages of the values measured at 30, 60 and 90 cm depths, to be compared to the comfort threshold of -80 kPa. The cumulative *R + I* course appears as grey areas at the bottom of each sketch, with values read on the right axis, while irrigations are depicted by grey drop symbols. The vertical dotted lines (in green) indicate flowering dates (VT and R1). On the (a), (b), (c) and (d) sketches, the *SWP* values provided by the Inter-Panels (IP) sensors are plotted as dotted lines while those provided by Under-Panel (UP) sensors are plotted as solid lines.

### 5.2.3 Phenology and vegetative growth

Table 5-2 shows the days after sowing (DAS) to reach emergence (VE), tasseling (VT), and silking (R1) phenological growth stages for the seven treatments, during the 2020 and 2021 seasons. We observed two general trends, (i) **a delay for all shaded plots** compared to the FULLSUN conditions (whatever the irrigation treatment) in the emergence and flowering stages (5-11 days, depending on the shading rate), and (ii) in all cases when **combining moderate water stress and a moderate shade** (DAV\_DI and AVhalf\_DI plots), the delay was **larger** than in fully irrigated or FULLSUN conditions.

In both the 2020 and 2021 seasons, the delays were 5-7 days for **emergence** in the moderate shade treatments (DAV and AVhalf, shading rate of around 30-35%) and **about 10 days** in the

high shade (AVfull, shading rate of around 50%). The delay in VT and R1 **reproductive stages** under **moderate shade combined with deficit irrigated** conditions were of **4-7 days** (in VT) and **4-11 days** (in R1), while in **fully irrigated** conditions, this delay was of **4-5 days** and **3-5 days**, respectively (also under moderate shade). Additionally, **no difference** was observed **between DAV and AVhalf** (except for R1 in 2021). The delay to reach the VT stage under **FULLSUN** and **deficit irrigated** conditions was of **2-4 days** when compared to **FULLSUN** and **fully irrigated** conditions, showing the independent effect of deficit irrigation increasing the delay of reproductive stages. This analysis does not hold for NI conditions, either reaching the VT or the R1 stages during the two years of monitoring, whatever the shade level.

Table 5-2. Days After Sowing (DAS) to reach emergence (VE), tasseling (VT), and silking (R1) crop stages for the seven treatments during the 2020 and 2021 seasons. The “not reached” indication means that less than 50% of plants had flowered. The symbols in the stress column indicate the level of stress (moderate shade = ●, high shade = ●●; deficit irrigated = †, not irrigated = ††). Not all the stress combinations shown in Table 1 were studied in 2the 020 and 2021 seasons.

Shade	Irrigation	Stress	2020			2021		
			VE	VT	R1	VE	VT	R1
FULLSUN	FI	Control (no stress)	12	87	87	11	87	87
FULLSUN	DI	†	12	91	95	11	89	89
FULLSUN	NI	††	12	Not reached	Not reached	11	Not reached	Not reached
DAV	FI	●	17	91	91	18	94	94
DAV	DI	●†	17	95	98	18	94	98
AVhalf	DI	●†	17	95	98	18	94	99
AVfull	NI	●●††	22	Not reached	Not reached	21	Not reached	Not reached

Concerning **vegetative development**, Figure 5.9 shows the GDD and Rg-tot needed to develop a new leaf during the 2021 cropping season (the only season with leaf number monitoring). The main interpretations of Figure 5.9 are: (i) as expected, the cumulated **thermal time** (GDD) and radiation (Rg-tot) variables were well associated with the leaf number, as the analyses have been conducted separately; (ii) the slope of the lines (**phyllochron**) for AV were lower than those in FULLSUN conditions, indicating that leaves in shade appear slower than in FULLSUN conditions and (iii) the key determinant for the **number of leaves** appears to be the **shading** or non-shading conditions while the **irrigation** strategy plays a limiting, **cut-off role**, as non-irrigated treatments prevented full crop development. The final number of leaves was optimal in the irrigated **FULLSUN** plots (**15-16 leaves** for the FI or DI treatments), while in the shaded **AV plots** the maximum number of leaves was **limited to 12**.

The effect of panels on the **phyllochron** (*PHY*) was clear (Figure 5.9a): in the non-limiting light conditions (**FULLSUN**), the *PHY* value was **64 °Cd leaf<sup>-1</sup>**, while in the AV plots the *PHY* values increased with increasing **shading rate**: **79 and 81 °Cd leaf<sup>-1</sup>** in the DAV and AVhalf plots respectively (**moderate-level shade**) and **95 °Cd leaf<sup>-1</sup>** in the AVfull plot (**high-level shade**). These results are consistent with those of Birch et al. (1998) who reported increased phyllochron values with reduced irradiance. The *PHY* value reported in not-limited conditions (FULLSUN\_FI) is not far from the values reported by Verheul et al. (1996) among different



maize cultivars (between 38 and 52 °Cd leaf<sup>-1</sup>). The irrigation strategy did not affect *PHY* values (analysis not shown).

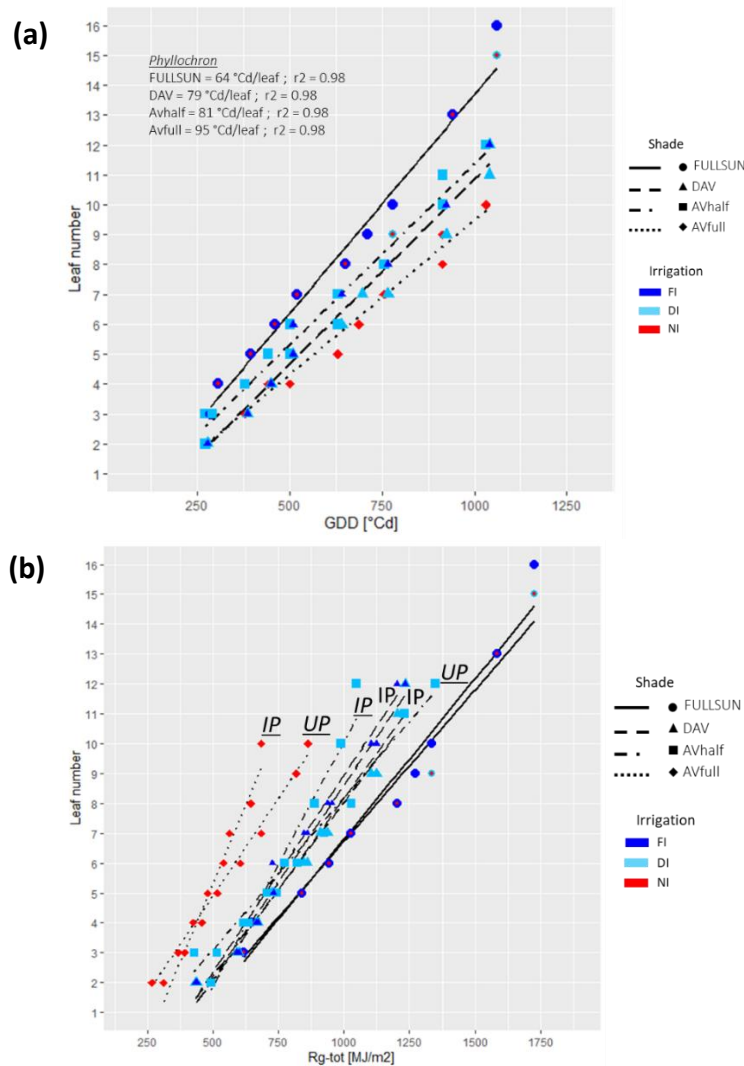


Figure 5.9. Leaf number associated with (a) cumulated Growing Degree Days (GDD) and with (b) cumulated radiation ( $Rg\text{-tot}$ ) in 2021, for the different shading conditions: FULLSUN (circles and solid lines), DAV (triangles and dashed lines), AVhalf (squares and dot-dash lines), and AVfull (diamonds and dotted lines); crossed with irrigation strategies: Fully Irrigated (FI, in dark blue), Deficit Irrigated (DI, in light blue) and Not Irrigated (NI, in red). In (b): IP = Inter-Panels UP = Under-Panel positions.

Consistently, **Leaf Area Index (LAI)** evolution largely depends on both radiative and hydric conditions, as shown in Figure 5.10 with the maximum values of LAI for all experimental conditions (2019 to 2021), and the seasonal variation of LAI during the year 2020 (the most complete data). As expected, the **maximal LAI ( $LAI_{max}$ )** values **decrease** when less radiation is present and (or) when water is limited during the course of the season (Figure 5.10a,b,c), the latter also affecting the shape of the LAI curve (Figure 5.10d). As an example, in the presence of pronounced **water stress** (red curves), the LAI curve was lower for high shading rates (AVfull) than for FULLSUN conditions, suggesting that the **presence of panels is not sufficient to compensate for the effect of water deficit**. In coherence, similar dynamics are observed in AV plots with similar shading rates (DAV, AVhalf) and similar irrigation amounts, suggesting that the dynamic rotation of panels in DAV had no significant effect on LAI

dynamics. Finally, similar *LAI* dynamics were observed for moderate shading rates (DAV\_FI) or moderate water deficit (FULLSUN\_DI) which seems an interesting result for **modeling purposes**, suggesting introducing an overall stress indicator affecting the evolution of *LAI*.

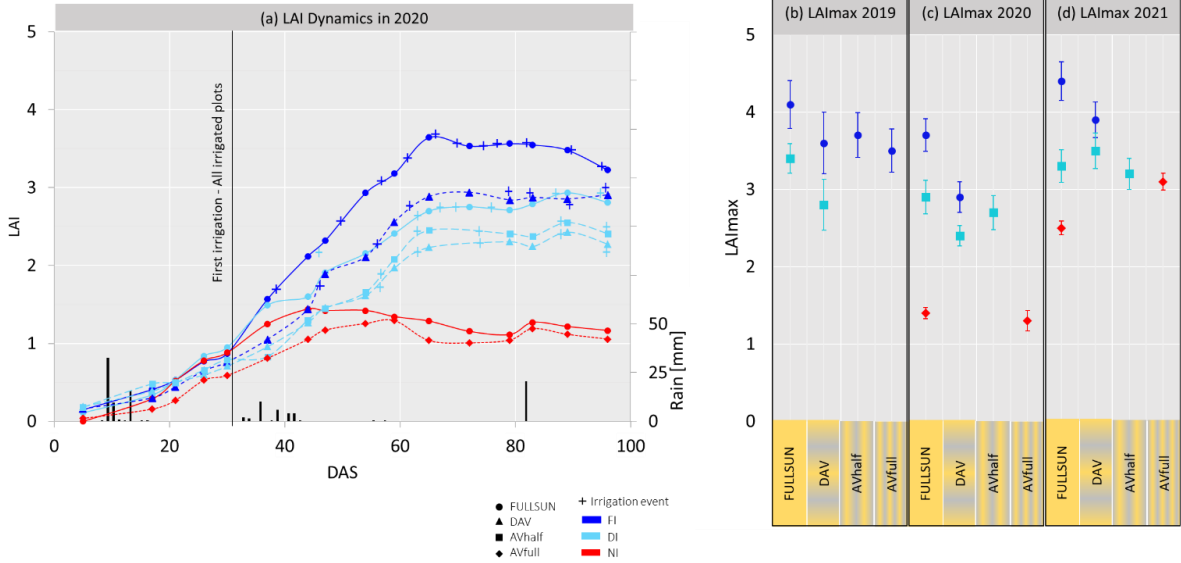


Figure 5.10. Leaf Area Index (*LAI*) dynamic curves for the 2020 cropping season (a) and maximum values of *LAI* (*LAI*<sub>max</sub>) for the three cropping seasons, 2019 (b), 2020 (c) and 2021 (d), for the different combinations of shading (FULLSUN in circles, DAV in triangles, AVhalf in squares and AVfull in diamonds) crossed with irrigation strategies (FI – Fully Irrigated, in dark blue, DI – Deficit Irrigation, in light blue, NI – Not Irrigated, in red). In sketch (a) the continuous lines represent the FULLSUN plots and dotted lines the shaded treatments, the crosses indicate irrigation events (in general, 40 mm for FULLSUN and 30 mm for DAV and AVhalf), and the histograms indicate rain amounts, read on the right axis. In sketches (b), (c) and (d), points indicate average values ± standard error.

### 5.2.4 Stomatal responses to shade

Figure 5.11 depicts the typical dynamics of measured **Photosynthetically Active Radiation (PAR)**, **Leaf Temperature ( $T_{leaf}$ )**, **Net Assimilation Rate ( $A$ )**, and **Leaf Stomatal Conductance ( $g_s$ )** of maize leaves, in different conditions: FULLSUN fully irrigated (Figure 5.11a), DAV fully irrigated in the two UP and IP positions (Figure 5.11b,d) and DAV deficit irrigated only in IP position (Figure 5.11c) that can be compared to Figure 5.11d. In non-limiting conditions (Figure 5.11a), we observe that the values of all measured variables increased from the beginning of the measurements to reach a **maximum near midday**, before a gradual decrease takes place to the end of the day, while in AV plots we observe the same trends but with the shading breaks, from a few minutes to few hours, in all processes measured. More specifically, the dynamics of  $A$  and  $g_s$  were highly correlated to those of  $PAR$ , in shaded or FULLSUN conditions, for fully irrigated or deficit irrigation conditions and whatever the plant position to the panels (IP or UP). The effects of panels can also be observed on  $T_{leaf}$ , but the changes were less pronounced.

Furthermore, the experimental data show that **plant reaction to PAR** changes is **neither immediate nor unique**. During brief shadings, the stomata had insufficient time to adapt to  $PAR$  variations (see Figure 5.12, which is a close-up of Figure 5.11d) while in the case of prolonged shading, the time needed to adapt was ca. 10 minutes. Figure 5.12 shows that our data is coherent with those shown by Percy et al. (1997), indicating that responses of photosynthesis to increases in irradiance are not instantaneous and with the study of

Meidner and Mansfield (1965) who showed evidence that the processes of stomatal opening and closing are different in nature and that one is not simply a reversal of the other.

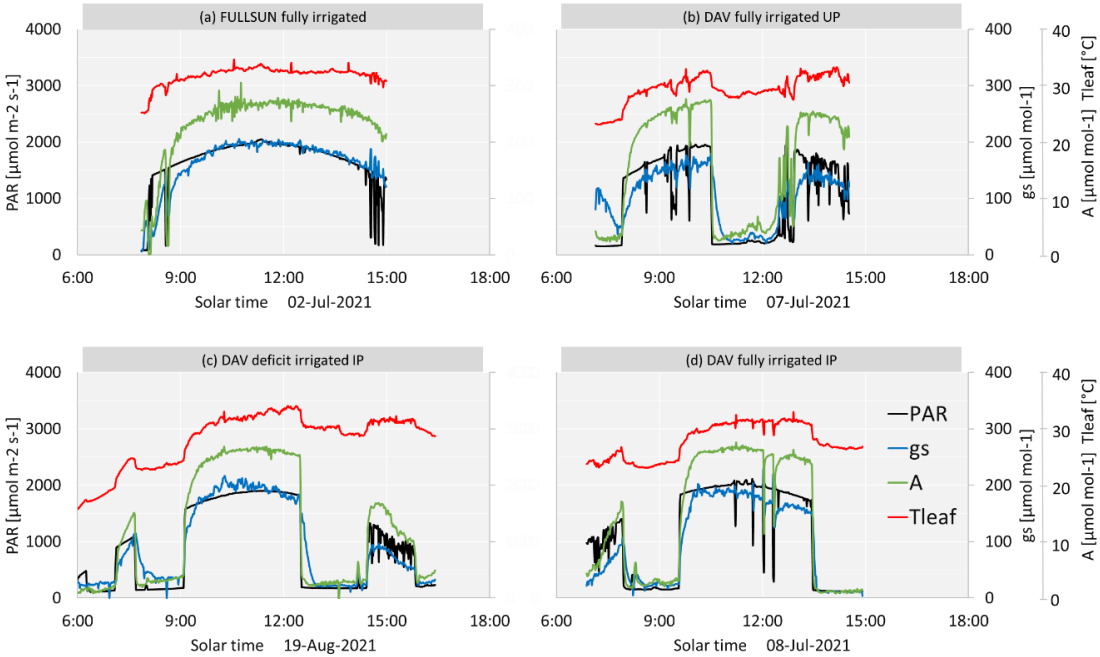


Figure 5.11. Diurnal dynamics (6:00 to 18:00) of photosynthetically active radiation (PAR, in black), stomatal conductance ( $g_s$ , in blue), net assimilation rate ( $A$ , in green), and leaf temperature ( $T_{leaf}$ , in red) measured on maize leaves by a Portable Photosynthesis System (1-minute timestep) in different clear-sky conditions during the 2021 cropping season: (a) FULLSUN fully irrigated, (b) DAV fully irrigated (UP position), (c) DAV deficit irrigated (IP position) and (d) DAV fully irrigated (IP position). The date of measurement is indicated at the bottom of the sketches.

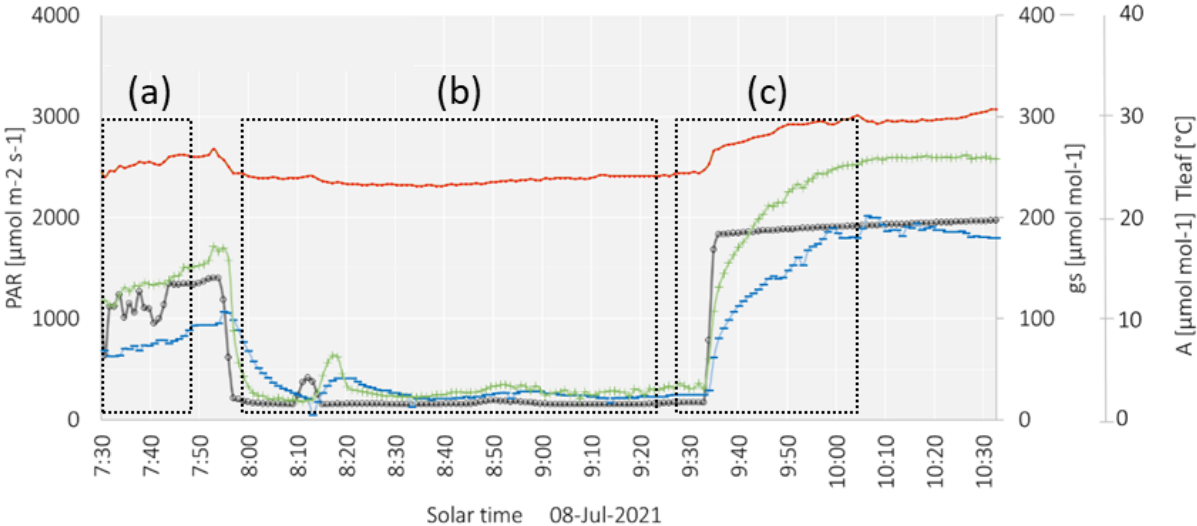


Figure 5.12. Close-up on Figure 5.11d, seeking the effects of brief shading (a), prolonged shading (b), and a sharp increase in incoming radiation (c). See the legend of Figure 5.11.

5.2.5 Crop production and water productivity

**Total Dry Matter (TDM)** and **Dry Grain Yield (GY)** are provided in Figure 5.13 for the three seasons. The main observations of this figure are: (i) As for the *LAI* values, both *TDM* and *GY* were **reduced** when **irrigation** and (or) **radiation** were **reduced**, thus in comparison with the FULLSUN and fully irrigated conditions (Figure 5.13a). (ii) **Moderate shading** rates in DAV (35%) and AVhalf (30%) under fully irrigated conditions (Figure 5.13b,c) **reduced irrigation** amounts by **19-35%**, while for **high shading rate** (AVfull, Figure 5.13d) irrigation was reduced by **47%**. (iii) The *TDM* and *GY* production was **equivalent** in **DAV** and **AVhalf** under **fully irrigated** conditions, and this production was, at once, comparable to that under **FULLSUN** and **deficit irrigation** conditions. (iv) When **combining moderate water and shade stresses** (DAV and AVhalf under deficit irrigated conditions) the **reductions in TDM** were **40-53%** and **22-51%** in *GY*, indicating **lower reductions in GY compared to TDM**. (v) Finally, **not irrigated** treatments (whatever the shade level) produces **higher TDM and GY reductions** (by **71-80%** and **66-83%**, respectively), showing the **cut-off effect** on crop development of **high-water stress**.

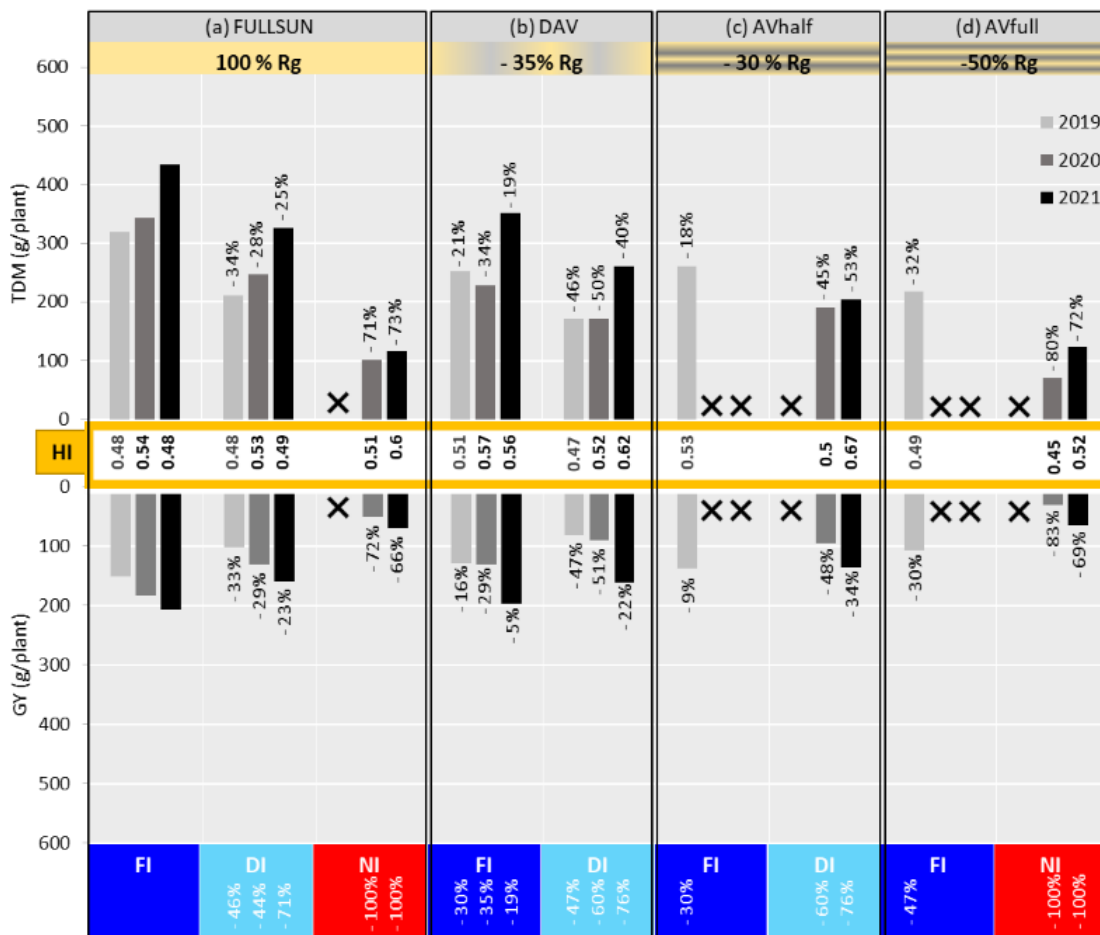


Figure 5.13. At the top, Total Dry Matter (TDM), and at the bottom Dry Grain Yield (GY) for the (a) FULLSUN, (b) DAV, (c) AVhalf, and (d) AVfull plots, for the three cropping seasons (2019, in light-grey; 2020 in dark-grey and 2021 in black). The three irrigation strategies (FI – Fully Irrigated, DI – Deficit Irrigated, and NI – Not Irrigated) conditions. The percentages over the histograms indicate the relative reduction compared to the FULLSUN fully irrigated plot, in the same year. Harvest Index (HI) is indicated in the middle of the figure (the yellow square). The X symbol indicates that this combination of stress was not studied in the current season.

Table 5-3 gathers the final indicators for the **water budget** and **crop production**, for the different plots and treatments. **Water Productivity of Irrigation (WPI)** was **higher in shaded plots** under irrigated conditions, especially in deficit irrigated plots. However, in terms of **Water Productivity (WP)**, which also considers the rainfall inputs, we observe the **inverse trend**. Finally, the values of the **Harvest Index (HI)** varied between **0.48 to 0.57** in **fully irrigated plots**, between **0.47 to 0.67** in **deficit irrigated plots** and between **0.45 to 0.6** in **not irrigated plots**. Thus, **HI** did **not** seem to be **impacted by shade**. The values of the *HI* varied between 0.48 to 0.6 in FULLSUN plots, between 0.47 to 0.67 in DAV and AVhalf (moderate shade), and between 0.45 to 0.52 in AVfull (high shade). These values correspond to values reported in maize (0.20 to 0.56) for different growing conditions (Ion et al., 2015). However, our estimations were based only on aerial *TDM* without considering the underground biomass (the root system was not harvested). Considering root mass in the estimations should decrease *HI* in all plots.

Table 5-3. Crop growth and production indicators for 2019, 2020 and 2021 cropping seasons:  $LAI_{max}$  is the maximum value of LAI recorded from LAI-2200C – LICOR measurements. Values of LAI allometric measurements realized at the end of the 2021 season are presented in parenthesis. TDM and GY are, respectively, the mean weight of total dry matter of aerial parts and dry grain yield of the ears from 40 plants sampled at each plot, and HI is the harvest index computed for each plot (GY/TDM). WPI is the Irrigation Water Productivity computed as TDM (in kg) divided by I (in  $m^3$ ), considering a plant density of 8.3 plants by  $m^2$ . WP is the Water Productivity, with the same logic as WPI but using R+I in the denominator. For legibility, the P value is reported only for AV plots related to FULLSUN (under similar irrigation conditions). After TDM and GY variables, the same letter (ns columns) indicates no significant difference between means (Turkey HSD test,  $P < 0.05$ ).

Shade	Irrigation	$LAI_{max}$ [ $m^2/m^2$ ]	TDM			GY			HI [-]	WPI [ $kg/m^3$ ]	WP [ $kg/m^3$ ]
			[g/plant]	ns	P	[g/plant]	ns	P			
<b>2019</b>											
FULLSUN	FI	4.1 ± 0.3	318.8 ± 104			151.9 ± 43	a		0.48	7	5
FULLSUN	DI	3.4 ± 0.2	210.2 ± 77	b		101.7 ± 41	b		0.48	8.5	4.9
DAV	FI	3.6 ± 0.4	252.2 ± 79	a	< 0.0001	128.3 ± 35	a	< 0.0001	0.51	7.9	5.1
DAV	DI	2.8 ± 0.3	172.0 ± 67		< 0.01	81.2 ± 39		< 0.001	0.47	7.2	4.1
AVhalf	FI	3.7 ± 0.3	260.9 ± 66	a	< 0.0001	138.4 ± 36	a	< 0.050	0.53	8.2	5.2
AVfull	FI	3.5 ± 0.3	217.0 ± 51	b	< 0.0001	106.7 ± 29	b	< 0.0001	0.49	9	5.2
<b>2020</b>											
FULLSUN	FI	3.7 ± 0.2	343.1 ± 86			183.9 ± 33			0.54	7.3	4.4
FULLSUN	DI	2.9 ± 0.2	246.9 ± 84	a		130.7 ± 40	a		0.53	10	4.4
FULLSUN	NI	1.4 ± 0.1	107.6 ± 35	c		51.8 ± 35	c		0.51	---	3.2
DAV	FI	2.9 ± 0.2	227.9 ± 48	a	< 0.0001	130.2 ± 31	a	< 0.0001	0.57	7.3	3.6
DAV	DI	2.4 ± 0.1	193.0 ± 63	b	< 0.0001	89.4 ± 34	b	< 0.0001	0.52	9.3	3.4
AVhalf	DI	2.7 ± 0.2	190.0 ± 41	b	< 0.0001	95.5 ± 32	b	< 0.0001	0.5	10.2	3.8
AVfull	NI	1.3 ± 0.1	69.3 ± 30	c	0.157	31.4 ± 26	c	0.430	0.45	---	2.2
<b>2021</b>											
FULLSUN	FI	4.5 ± 0.1	434.2 ± 73			206.9 ± 30	a		0.48	14.6	6.3
FULLSUN	DI	4.1 ± 0.1	326.5 ± 99	b		160.0 ± 44	b		0.49	38.3	6.9
FULLSUN	NI	2.4 ± 0.2	116.6 ± 48	c		70.5 ± 22	c		0.6	---	3
DAV	FI	2.6 ± 0.1	352.1 ± 86	b	< 0.0001	196.3 ± 47	a	0.923	0.56	14.7	5.6
DAV	DI	2.2 ± 0.1	260.6 ± 53		< 0.01	161.2 ± 52	b	0.999	0.62	36.2	5.7
AVhalf	DI	2.4 ± 0.1	203.6 ± 61		< 0.0001	135.7 ± 38	b	0.147	0.67	28.3	4.4
AVfull	NI	1.7 ± 0.1	123.5 ± 41	c	0.999	64.0 ± 36	c	0.999	0.52	---	3.2



## 5.3 DISCUSSION

### 5.3.1 Phenological delay

Plant emergence was delayed proportionally to shade intensity as shown in Table 5-2. Plant emergence in maize is mainly influenced by soil temperature among other factors (soil water content and seed depth). In our study, the only difference between plots during seeding was shading, causing a reduction in soil temperature, and directly impacting emergence time. Soil temperature reduction Under-Panels in the Agrivoltaic platform of Lavalette was not presented here but had already been reported by Marrou et al. (2013a,b) both in irrigated and not irrigated conditions. A reduction in soil temperature was also described under field AV conditions in Germany (Armstrong et al., 2016) and Italy (Amaducci et al., 2018), suggesting a generalized effect of shade-cooling soil temperature (at least, in temperate and Mediterranean conditions).

The delay observed in flowering stages VT and R1 were maintained in a similar proportion to shade such as in emergence. The first hypothesis that could be derived from this fact is that the earlier delay in emergence may be the principal factor affecting the subsequent phenological development (leaf stages and flowering). In this sense, Earley et al. (1966) also reported flowering delay in maize under shading but when shade was applied during vegetative growth (avoiding the delay in emergence such as in our experiments). Thus, the delay in flowering was probably more related to leaf stages development, also affected by shade. Indeed, a reduced final number of leaves (Figure 5.9), may explain the delay in VT and R1 stages, as the time elapsing to flowering from emergence is associated with the final number of leaves per plant (Tollenaar et al., 1979). Moreover, (Birch et al., 1998a,b) also reported similarly a reduction in the number of leaves under 55% to 73% level of shade.

The inhibition of flowering due to severe water stress was clear, but moderate stress (such as in deficit irrigated plots) seems not to affect VT. However, this can lead to a slight delay between VT and R1 (in shaded and in unshaded conditions), which was not observed in fully irrigated conditions. This effect was more evident in 2020, likely due to the drier conditions of the season. This delay between VT and R1 is related to the Anthesis—Silk Interval (ASI), one of the best indicators of how plants respond to stress (water, light, nutrients) during flowering. A similar response of maize was described by Nesmith and Ritchie (1992) under hydric deficit conditions. In our experiments, we did not observe a delay between VT and R1 under shade, suggesting that the presence of panels in AV does not influence ASI.

### 5.3.2 Vegetative development

In a more detailed analysis of vegetative development, one of our main findings is the influence of shade on phyllochron (Figure 5.9a). The emphasis is placed here on the fact that more temperature is needed for a new leaf formation when less radiation is available. Similar results were discussed by Birch et al. (1998a,b) in both controlled atmosphere and field conditions. They reported that shading lengthened phyllochron causing an increase of 2-4 °Cd for each MJ decreased in daily PAR. Since leaf appearance (phyllochron<sup>-1</sup>) is commonly linked only to thermal time, it was not expected that soil water or light influenced phyllochron.

From our results, in the case of soil water, we can reaffirm that this factor (water) does not influence phyllochron. The mentioned influence of shade on phyllochron led us to propose the relationship of leaf appearance to “radiation time” (cumulated *Rg-tot*) instead of thermal



time (cumulated *GDD*) to compare both relationships separately (Figure 5.9b). It was interesting to observe that leaf appearance showed a similar (linear) dependence on radiation such as with thermal time. This was probably due to the close relationship between radiation and air temperature and because the leaf's (and plants) temperature is also strongly affected by radiation. Moreover, when computing *PHY-r* (phyllochron using radiation instead of temperature) and distinguishing between data obtained in UP (under-panel) and IP (inter-panel) positions in AV plots, we observed differences in *PHY-r* values between the UP and IP in the fixed devices AVhalf and AVfull. These differences could be ignored (almost certainly) when using a classical thermal time relationship, because of the slight variations in air temperatures recorded Under-Panels compared to FULLSUN (see Figure 5.6 and Figure 5.7).

This last statement suggests that one could use *PHY-r* instead of *PHY* in systems with strong spatial heterogeneities in radiation. This may open new pathways to define the determinants and controls of crop development, especially for spatial-discrete crop modeling in AV systems (and probably also in agroforestry). Another way to improve phyllochron estimation in AV systems may be the use of plant (or leaf, stem or canopy) temperatures instead of air temperature since this temperature is more impacted by the presence of panels (directly determined by energy balance) than the mean air temperature, as suggested by leaf temperature dynamics (see Figure 5.11). We could not deepen this idea without monitoring daily plant-based temperatures, but we suggest exploring it in further experiments or by modeling (i.e., Blonder and Michaletz, 2018) to improve carbon and water fluxes estimations. Therefore, models using thermal time could be enriched by including shade effects on phyllochron or energy balance to better aggregate the possible misrepresented physiological responses of the crops in AV.

The complementary analysis of vegetative growth using Leaf Area Index (*LAI*) dynamics (Figure 5.10) and maximal values of *LAI* (*LAI<sub>max</sub>*) led us to affirm that water deficit and shade have more impact on individual leaf size than on leaf appearance, thus in total leaf area of the plant (and of the plot). This response is well-known and related to plant adaptive traits, most of them showing that water and carbon emerge as the main limiting factors of leaf expansion (Pantin et al., 2011), even if the literature remains controversial about their respective contributions to the final leaf area. Some of the more cited responses to stress (water, shade, nutrients) at the leaf level are the reductions in leaf area, mass, and thickness (Givnish, 1988) and photosynthetic characteristics modifications (i.e., Ren et al., 2016).

Concerning the effects of the “Solar Tracking” panel rotation strategy implemented in DAV compared to AVhalf plots (having different intraday patterns but similar daily total irradiance as shown in Figure 5.6 and Figure 5.7) we did not observe a clear difference in *LAI<sub>max</sub>* values (Figure 5.10) in fully irrigated conditions, neither in deficit irrigated conditions. This is in contrast with the inverse relationship between the optimal maximum photosynthetic capacity and the frequency of low-to-high light transitions reported by Retkute et al. (2015), who suggest that the effects of shade in leaf growth will depend also on the intraday patterns of shade. The effects of dynamic panels in leaf appearance were neither affected in DAV compared to AVhalf in Figure 5.9.

These findings suggest that vegetative growth (i.e., leaf appearance and canopy size) at the plot scale was not strongly affected by the spatial heterogeneity of radiation transmission to the crop. To complement this analysis, specific allometric measurements of *LAI* in the UP and IP positions could be used to describe canopy growth heterogeneities, especially in fixed-AV

installations characterized by high crop irradiance heterogeneity. Also, we encourage the general use of *LAI* to describe vegetative development in AV systems (i.e., for modeling purposes) since this index is a critical variable in processes such as photosynthesis and respiration and allows to capture the effects of both stresses analyzed here when we do not require a “fine” spatial discretization of crop growth.

### 5.3.3 Crop production

Concerning the final agricultural production, we observed in Figure 5.13 the negative effects of irradiance reduction and (or) water stress, as documented by several authors in different maize-shaded experiments (e.g., Mbewe and Hunter, 1986; Yuan et al., 2021; Zhang et al., 2006) and in other crops that are not tolerant to shade grown in AV (Weselek et al., 2019). The reduction of the maximal and final values of *LAI* combined with the higher phyllochron (lower leaf appearance rate) caused by the panels (Figure 5.9 and Figure 5.10) likely affect light interception and seem prone to explain the reported negative effects on the final *TDM* and *GY* values. Furthermore, yield production studies have shown that the effects of stress depend on the type, severity, and duration of the stress, as well as on the stage of development of the plant when the stress is applied, the reproductive stages (VT and R1) being the most detrimental to dry grain yield (Tollenaar, 1977). In particular, grain filling is said to be affected at the start of the critical period of grain set formation if solar radiation or (and) temperature sharply declines during this period (Otegui et Bonhomme, 1998) thus reducing the number of grains per grain set (Loomis and Connor, 1992).

In all of our shaded plots, the shade was permanent, explaining the high yield reductions as documented by Ren et al. (2016), who also reported the lowest reduction of net photosynthetic rate when shade was applied only from the sixth leaf stage (V6) to silk (R1). In turn, Earley et al. (1966) showed that shading for 21 days during the reproductive phase was more detrimental to grain production per plant than shading for longer periods during vegetative and maturation phases. They also reported that a reduction of light from 100 to 70% essentially eliminated the development of the second ear, which was similar to that in our experiments.

Concerning the effects of water, in Figure 5.8 we can observe that water depletion was high in the pre-flowering and flowering periods for deficit irrigated treatments, affecting crops during this sensitive period. In not irrigated maize plots (whatever the shading rate) the effect of water stress, particularly in 2020 (Figure 5.13) was evident, confirming the sensitivity of maize to the erratic behavior of rains (Campos et al., 2004). We highlight the strong effect of water deficit in not irrigated plots on flowering failure (under shade or not), affecting crop production. However, the data shown in Figure 5.13 for FULLSUN not irrigated plots correspond to “survival” plants in the plot, where most of them died, while in AVfull most of them were still green at harvest. This seems to support the results reported by Amaducci et al. (2018), who suggest higher and more constant average maize yields under shade compared to unshaded plots under rainfed conditions (their results come from simulations carried out with climate data over 37 years).

In maize, grain filling shows a dependence on Anthesis—Silk Interval (ASI) and is particularly associated with a reduction in photosynthate formed during grain formation (Edmeades et al., 2000), probably impacting grain yield in deficit irrigated plots. The smaller relative reduction of *GY* (in comparison with *TDM*) in the fully irrigated AV plots and some of the deficit irrigated plots shown in section 5.2.5, can be explained by the photosynthetic acclimation process

(Hirth et al., 2013) and possibly also by the internal mechanisms of maize plants to recycle the surplus of water during grain filling (Zhang et al., 2022). Photosynthetic acclimation is how plants alter their leaf composition and physiology over time to enhance photosynthetic efficiency, productivity, and allocation.

We hypothesized that the maize plants adjust the light-response characteristics to balance the efficient use of absorbed energy in fluctuating light (varying in both intensity and frequency) to maximize daily carbon gain and maintain a specific level of photosynthesis. This affects leaf growth but promotes at the same time a concentration of assimilates on grain formation, reducing the impact on *GY*. However, this hypothesis should be taken carefully, because in C4 crops, photosynthesis is less phenotypically “plastic” than C3 photosynthesis, and this may contribute to the more restricted adaptation to intermittent light (Sage and McKown, 2006).

The water recycling mechanism of maize plants (by back-flow capacity via the pedicel phloem-xylem system connecting grain and cob) could allow the storage of the “surplus water” applied during water comfort periods (for example just after an irrigation event) in cob tissue, ensuring water availability for grain filling during slight or moderate water stress in deficit irrigated plots. Thus, complementary measurements of photosynthetic rates would be needed for the evaluation of this specific effect of shading considering the effect of growth stages and water status of the plant on the photosynthesis response of maize.

In 2021 (Table 5-3), we observed smaller reductions of *TDM* and *GY* in all cases, even when water irrigation reductions on deficit irrigation (DI) treatments were higher (71-76%) compared to 2019 and 2020 (44%-60%). This is because 2021 was a rainy year with significant rainfall events throughout the season (323.5 mm of cumulated rain during the crop season, compared to 264 mm and 149.5 mm during 2020 and 2019, respectively). This is confirmed by Figure 5.8 in which we observe that water depletion was high around DAS 80 to 100 (pre-flowering and flowering period) in deficit irrigated plots in 2020.

Hence, deficit irrigated plots were less stressed during vegetative, pre-flowering, and grain-filling stages in 2021, which are the most sensitive stages to stress (shade or limited water) as shown by several authors (i.e., Tollenaar, 1977). This resulted in higher production with fewer irrigations in 2021. However, grain yield production in stress conditions depends on the type, severity, and duration of the stress, as well as on the stage of development of the plant when the stress is applied, highlighting the need for more trials with stress applied in different stages to complete the analysis.

#### 5.3.4 Water use

The shading patterns from the panels improved the water status of maize, reducing applied water in fully irrigated plots (Figure 5.13), in a similar proportion compared with previous results in other crops studied under similar AV systems, such as lettuce (Elamri et al., 2018b) and apple trees (Juillion et al., 2022). Higher *WPI* in deficit irrigated plots (shaded or not) compared with fully irrigated conditions shown in Table 5-3 supports previous data showing higher yields per unit of irrigation water applied in maize under regulated deficit strategies (Huang et al., 2011; Zou et al., 2021). Improved *WPI* in AV (in fully irrigated conditions) reported in Table 5-3 is probably related to the capacity of AV systems to (i) reduce reference evaporative demand ( $ET_0$ ) under shade (Figure 5.4), and (ii) to slow down soil water depletion (Figure 5.8), both reducing the actual evapotranspiration of any crop (not measured directly in our study).

An interesting fact that we observed in Figure 5.8 is that in fixed AV systems (for example in the AVhalf plot in Figure 5.8b), soil water conservation was strongly different depending on the UP (under-panel) or IP (inter-panel) positions when radiation distribution is heterogeneous. Indeed, in fixed devices, the rain redistribution is always impacted by solar panels, with a high concentration of intercepted rain onto the soil at the lower edge of the solar arrays and much less runoff to the soil area under the panels, as shown by Elamri et al., (2018b) in the same experimental platform of our study. They also mentioned that this redistribution is, to some extent, attenuated within the soil due to lateral transfers at the soil surface (ponding), and within the soil profile where significant lateral dispersion coexists with gravity.

This underlines the relevance and the potential benefits of tilting-angle panels (or other dynamic structures) to homogenize altogether (i) transmitted radiation (as shown in Figure 5.7), (ii) rain redistribution (as demonstrated by Elamri et al., 2018b) and (iii) soil water depletion (as demonstrated in Figure 5.8). This is probably related to reduced crop development and growth in IP areas (thus reducing root activity and reduced water uptake capacity). Root development and underground biomass were not measured in our experiments; however, it is well known that shading has a strong impact on the development of roots in the upper soil layer, significantly decreasing the root morphologic and activity indices (Gao et al., 2017b). A similar effect on soil water conservation is observed in finely textured soils, by making soil water available at critical stages of maize development (Huang et al., 2011).

#### 5.3.5 Some considerations to interpret the experimental results.

It is important to note that the different shading patterns implemented for this experiment in the DAV plot represented only the so-called “Solar Tracking” strategy implemented in our experiments, which is a shading strategy devoted to maximizing light interception and not favoring crop production. In addition, the fixed AV devices studied here are not the only configurations that could be implemented, since a multitude of other possibilities exist in terms of panels’ orientation, spacing, dimensions, height, and movements (degrees of freedom). Our experimental designs raise questions about the potential to generalize results because the shade applied could be different in other configurations, inducing different crop responses. Thus, further studies are necessary to evaluate different shading strategies, particularly in DAV devices, adapting the tracking panels strategy (and shading rate) to the different phenological stages, intending to minimize the effects of both stresses studied here.

Another consideration is the evaluation of the level of water stress applied in these experiments. Water stress was not applied in a controlled way and was not quantitatively estimated (only considering water stress when soil water potential dropped to -80 kPa, the comfort limit for the silt-sandy soil texture of the site). Hence, this allows us to consider that there was virtually and qualitatively water stress but without a quantitative evaluation of the level of stress. In this sense, the use of proper indicators (such as the crop water stress index, CWSI) may be useful for this purpose. Also, CWSI may help to prevent water stress in AV systems and may be used for irrigation scheduling such has been demonstrated by several authors (Anda, 2009; Fattahi et al., 2018; Gu et al., 2021).

Finally, we aimed to analyze and illustrate contrasted cases, and especially to evaluate the differences between dynamic and fixed plots to draw some preliminary conclusions, hopefully, useful and generic enough for future modeling aims. Additionally, it is still difficult

to affirm that the crop responses shown here are specific to the radiation limitation in AV systems since there are many adaptation traits in plants that vary in response to radiation level and to other environmental factors, many of which are themselves correlated with radiation level (Givnish, 1988). Furthermore, different maize genotypes may respond differently to shading (Yuan et al., 2021), adding a feature to minimize crop loss production in AV by shade-tolerant genotypes. Late sowing dates (as in the 2019 cropping season) may decrease the source/sink ratio in maize (Bonelli et al., 2016), which can also help to explain the lower yield in 2019 (Figure 5.13).

## 5.4 CONCLUSIONS AND PERSPECTIVES

In this experimental study, it has been demonstrated that the maize crop growth and production responded to both independent stresses studied here (shade and deficit irrigation) in a combined but not cumulative way, compared to no-stress conditions (full-sun and fully irrigated). In general, a delay in crop development and a significant decrease in leaf area index, total dry matter and grain yield were observed in stressed conditions.

Regarding water use in AV systems studied here, we can conclude that shade has an interesting potential to increase irrigation water productivity (in both fully and deficit irrigated conditions) by reducing the water inputs (by up to 19-47% compared to unshaded plots under fully irrigated conditions) and by managing soil moisture (particularly in dynamic DAV systems). Thus, even if AV systems decrease crop yield, these systems have the potential to save water, especially in water-limited systems.

An innovative finding in terms of phenology was a strong association of leaf appearance to radiation, showed by an observed increase of phyllochron under shade. Due to the slight impact of panels on air temperature and thermal time, we consider that crop growth and production processes were probably more influenced by shading effects, exposing the relevance of radiative climate in phenology monitoring in AV systems. We then suggested that radiation may be included (in complement to thermal time) in phyllochron estimation in AV systems, particularly in crop modeling studies. Additionally, we did not observe a clear difference in leaf appearance (phyllochron) or leaf canopy area (*LAI*) between fixed and dynamic AV systems, concluding that the crop phenology and vegetative growth are more affected by the total irradiance received during the daytime than by the intraday dynamics of this radiation.

Another interesting conclusion is that at the leaf level, the responses studied here (stomatal conductance, net assimilation rate of CO<sub>2</sub> and leaf temperature) reacted in a well-correlated way to photosynthetically active radiation. This behavior opens new opportunities to optimize water use and shading strategies in further research by using a modeling approach. Crop modeling can be a valuable tool to assess numerous scenarios *in silico*, crossing the two principal drivers studied here: shading rate and irrigation, and applying these stresses in shade and/or in water-tolerant stages of maize, to find the “good” combination that could tackle the optimization target. However, adaptations of current formalisms may be implemented to consider the specific effects of intermittent shade in the crop processes at plot and leaf scales.

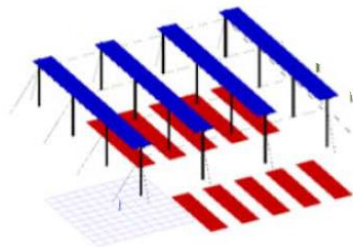
Also, specifically in the case of water budget modeling, the most frequently used crop models may be limited regarding their ability to simulate  $ET_0$  as showed by Kimball et al. (2019), constraining the accurate analysis of water fluxes. Finally, in the years to come, experiments on other field crops (wheat, barley, sorghum) will make it possible to study the impact of shade on crops presenting a different metabolism (C3 crops).



# CHAPTER 6

## MODELING MAIZE CROP UNDER DYNAMIC AGRIVOLTAIC SYSTEMS: A CASE STUDY WITH THE OPTIRRIG MODEL

*“One of the most insidious and nefarious properties of scientific models is their tendency to take over, and sometimes supplant, reality” – Erwin Chargaff*







# CHAPTER 7

## GENERAL DISCUSSION AND PERSPECTIVES



## CHAPTER 7 – GENERAL DISCUSSION AND PERSPECTIVES

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In this chapter, we delve into the implications and significance of the main findings gathered from the experimental axis (with maize crop) and the insights gained from the modeling axis (using generic crop models), critically discussing the perspectives to optimize AV systems concerning crop production and water use.

The field experiments conducted as part of this study and presented in Chapter 5, encompassed a diverse range of contrasted situations derived from combined irrigation and shading levels, affecting crop development and water budget. These experiments were designed based on the literature consulted in Chapter 3, to capture a representative picture of the interactions of shade and water stress and their impacts on field crops, with the main intention to assess the crop responses (in terms of crop production and water use) and the resilience of field crops to both stresses in AV systems.

Simultaneously, a case study to adapt a simple crop model was employed to complement the experimental work and provide a broader perspective on the possibilities to optimize maize (or other field crops) growth in AV systems. The state of the art in Chapter 4 the limitations of generic models to simulate field crops under shading conditions were analyzed, and simple key adaptations were proposed. In the case study presented in Chapter 6, simple adaptations to Optirrig were proposed and analyzed using experimental data. This holistic approach enabled us to simulate and predict maize production under different scenarios, facilitating a deeper understanding of the underlying mechanisms governing crop growth and productivity in AV systems and providing key elements for further research using generic crop models.

Through the integration of experimental data and modeling outcomes, this discussion chapter aims to address several critical research questions. We discuss if the AV systems represent a real solution face to water stress scenarios for field crops, discussing the results obtained for maize crops, but considering also the additional factors not considered in our experiments and that may be aborbed by modeling. Also, the modeling optimization perspectives are aborbed, discussing the justification of using more complex model approaches than those normally used in generic crop models by critically analyzing the results obtained from the maize field crops experiments and the case study using a simple crop model.

This discussion will not only contribute to enhancing the understanding of the main results reported here but also provide valuable hypotheses for further research and pave the way for future optimization works focusing on crop productivity and water used in AV systems, using as simple as possible modeling approach.

## 7.1 IS INTERMITTENT SHADING IN AV SYSTEMS A REAL SOLUTION TO IMPROVE WATER USE FOR MAIZE AND OTHER FIELD CROPS UNDER WATER SCARCITY CONTEXT?

### 7.1.1 Water reductions in AV systems: at what cost?

Water scarcity poses significant challenges to agricultural production and affects crop growth and development by limiting the availability of water for plants. As shown in Chapter 5, compared to unshaded conditions, the intermittent shading from panels in **AV systems** significantly **reduces water consumption** and the **soil water content depletion rate** by **reducing the climatic demands of evapotranspiration** in field crops. These results are similar to those reported for other crops (horticultural and perennial crops) studied under similar AV systems as shown by Elamri et al. (2018b) and Juillion et al. (2022), respectively. According to several authors, adopting innovative water-saving techniques is essential for maintaining food security (largely sustained by field crops production) due to increasing water scarcity under the changing climate scenario (Brauman et al., 2013; Kawano, 1990; Surendran et al., 2021). At first glance, this can allow us to state that AV systems represent a potential solution to managing water scarcity if we only consider **the large volumes** of water potentially saved in field crops under AV systems, representing benefits in terms of **local or regional water management**.

However, in agronomic terms, only **reduced water consumption** by crops carries little or no interest if it is not associated with **high or acceptable yields**. Such association of high (or moderate) reduction of water consumption with high (or moderate) yields has important implications for the **effective use of water**. From this perspective, the water savings should be considered as a benefice only if the **value of reduced yield** (in case it occurs) is less important than the **value of saved water**, which will be more probable to occur in cases when the cost of water is high and the yield value is relatively low. In such cases, the **economic value** of the conserved water may outweigh the potential loss in yield.

As well, the “benefits” of AV systems will be different depending on the agricultural system and the water availability context. Under a **water scarcity context**, the water resources may be limited in terms of volume or time affecting mainly **rainfed systems** (in which the water inputs depend only on the rainfall and **droughts** are a major threat) but may affect also **irrigated systems** by inducing **water shortages**, in consequence limiting **irrigation volumes** for crops or leading to unexpected **irrigation restrictions** (Chai et al., 2015). Hence, in any case in water scarcity conditions, any action helping to reduce water needs or to conserve available soil water for crops is essential to reduce (or avoid) crop water stress and consequences in agricultural production.

However, it is essential to evaluate each agricultural scenario individually, as the dynamics of water availability, crop types, local conditions, and economic factors can vary significantly. **Balancing water conservation** and **crop productivity** requires careful consideration of these factors to ensure the most efficient and sustainable use of water resources in agriculture. **Multidisciplinary approaches** (agronomic, ecological, legislative, economic, and societal) are required to analyze the holistic impacts of AV systems on crop water needs and yield to estimate the real benefits (or limitations) of implementing these systems for field crops, for example as shown by (Agostini et al., 2021).

### 7.1.2 The Interplay between shading, water use, and crop production: The role of water productivity and harvest index

As shown by this work, there exists an **interplay** between the effects of shading on crop yield and water use for annual crops under AV systems. This interplay must be explored and optimized if we want to guarantee the success of AV systems as a real solution to **improve water use** and minimize yield loss in non-water scarce conditions but also to **dampen and overcome** crop water stress in water-limited conditions (to **stabilize or ensure harvest** regardless of whether the yield is reduced by shade to a certain degree). Both water productivity of irrigation (**WPI**) and water productivity (**WP**), the latter considering the **total water incoming** the system (including the **effective rainfall and irrigation** amounts), are important and widely used indicators for evaluating and optimizing water use and crop production in agronomic systems. They provide insights into the effectiveness and sustainability of water use and agricultural practices for improving crop yields while minimizing water consumption (e.g., Ali et al., 2007; Barker et al., 2003; Gajić et al., 2018).

In this sense, another interesting result shown in this work (beyond the net reduction of water consumption in AV systems) is that **shading increased the WPI** in both, fully and deficit irrigated conditions. This improvement of **WPI** comes with an associated reduction of yield in AV systems. This confirms the general trends indicating that the higher the **WP** or **WPI**, the **lower the yield**, according to several authors (Ali and Talukder, 2008; Boutraa, 2010; Molden et al., 2010). That means that shading permits to increase in the unit of yield per unit of irrigation water applied (in maize) but also indicates that the total yield is decreased at the plot scale. These results are of important relevance to actual knowledge since there is any previous work assessing **WPI combining both limiting conditions** (water and radiation) for maize crops. Indeed, published research for all type of crops has mostly addressed **WPI** issues related to limited water supply and have usually not considered factors other than irrigation (Ritchie and Basso, 2008). The increase of **WPI** in the shaded plots presented in this work seems to be associated with irrigation water savings, approaching results evaluating **other techniques reducing irrigation** water amounts such as partial irrigation, deficit irrigation, or drip irrigation (e.g., (Ali and Talukder, 2008; Oweis et al., 2000; Sandhu et al., 2019).

However, in terms of **WP** (which includes both the **effective rainfall and irrigation** amounts), the reported results in this work showed that AV systems did **not improve WP in maize**. This differs from other studies reporting **WP** for different shaded crops: citrus trees (Alarcón et al., 2006), horticultural crops (Lorenzo et al., 2006), or grass (Adeh et al., 2018). The main reason is probably that maize is a **non-tolerant** crop to shade, but also an additional hypothesis is that the **levels of shade** applied to maize in these experiments were too high and maintained throughout the whole season (in particular during the shade-sensitive phenological stages), strongly **affecting yield**. The reductions of yield reported here (from 18% to 34% of yield reduction under reduced radiation of 30% to 50% in fully irrigated conditions) were similar to those reported by Ding and Su (2010) under **agroforestry** conditions but, surprisingly, considerably lower than those reported by Gao et al. (2020, 2017a) under **artificial shading** conditions using fixed screens decreasing yield by around 85% for two summer maize hybrids (under reduced radiation of 30% from seeding to physiological maturity stage).

Hence, it is clear that the “negative” **effects of shade** on crop yields should be **minimized** in AV systems and thus the arising question is if it is possible to increase **WP** and **WPI** without a significant yield reduction in field crops. There is no easy answer to that question since the response of field crops to shade and the plasticity of **WP** and **WPI** depend on various factors,

but the hypothesis is that there should exist **specific conditions** by merging shading and water management strategies in which this objective is reached for each crop and crop conditions. There are many examples where **yield** shows a **negative parabolic relationship** with the amount of **irrigation** or **radiation**. This suggests that the increase of irrigation or radiation initially leads to an increase in yield, but after a certain point, further increases in irrigation or radiation result in any increase of yield or even result in a decrease in yield (e.g., Trout and DeJonge, 2017; Yang et al., 2019). This is because excessive vegetative growth may lead to less root activity and a lower **harvest index** (Boutraa, 2010; Molden et al., 2010; Morison et al., 2008).

In this sense, the harvest index (*HI*), which refers to the ratio of harvested grain yield to total straw yield, is in general an important indicator used as a measure of crop efficiency (Singh and Stoskopf, 1971). In the experiments presented in Chapter 5, the *HI* was **slightly increased** for maize in the **AV systems studied** here (in **fully irrigated** conditions). This is probably because crops exhibit a higher photosynthetic rate during gradual soil drying conditions (such as in AV systems) than during fast soil drying conditions, according to Turner (1986). Hence, we can hypothesize that the reported yield losses in this thesis were possibly caused by an **inadequate strategy** of shading for this variety of maize, and thus other well-thought **shading strategies** (from dynamic devices) can improve *HI* and *WP* by **controlling the water stress** levels over time (e.g. by controlling the shading patterns), whilst **minimizing shade stress**.

Hence, further studies will make it possible to develop strategies for controlling the PV panels to adapt the water and radiation crop needs according to its phenological stages while considering the *WP*, *WPI* and *HI* indicators, but also factors such as the homogeneity altogether of transmitted radiation and soil water content and the specific tolerance of crops. However, the **exploration** and the **optimization** of the interplay between shading, water use and yield are difficult and costly to be implemented in field conditions, and thus such situations should surely be studied by **modeling methods**. In this sense, the use of **generic crop models** with minimal requiring inputs should be useful, specifically for management and for decision-making purposes in which accurate predictions are not required but indicative ones (Bergez et al., 2010; Janssen et al., 2010; Mir and Padma, 2017). The modeling analysis presented here in Chapters 4 and 6 should provide the basis for future works in this direction. Nonetheless, the main question (that is still unanswered) is: It is possible to reach the combined objective of minimizing yield losses whilst improving water productivity in AV systems? Probably yes and the discussion in the next section tries to shred this question.

## 7.2 HOW TO OPTIMIZE THE INTERPLAY BETWEEN SHADING, WATER USE, AND YIELD IN AV SYSTEMS? THE MANAGEMENT OF SHADING AND IRRIGATION STRATEGIES FOR OPERATIONAL PURPOSES

### 7.2.1 Which are the first-order variable forcing the interplay between water use and yield in AV systems? The perspective of parsimonious modeling for operational purposes

The interplay between **water use** and **yield** in plant physiology and agriculture is influenced by various factors, and radiation is just one of them. The **principal factors** are linked to crop characteristics (genetic traits of the different varieties and hybrids), environmental conditions, landscape and agricultural practices. Among them, **genetic characteristics** are the main factor influencing maize yield according to Miao et al. (2006). However, the genetic traits, soil characteristics, landscape and agricultural practices are not or are just minimally influenced by AV systems. **Soil characteristics** may be impacted by AV systems during the installation (compacting the surface layer of the soil) or by the rainfall redistribution effect of panels (by the erosion effects of the water flows draining from the panels and impacting soil, according to Elamri et al. 2018a). The **environmental factors**, and especially, the agrometeorological ones are the most directly impacted by panels (Mamun et al., 2022; Mavani et al., 2019). Concerning **agricultural practices**, irrigation is the most impacted by the panels since shade will undoubtedly affect water needs.

Focusing on environmental factors, **rainfall** variations, **average temperature** and **atmospheric CO<sub>2</sub>** are the main influencing crop yields according to Liliane and Charles, (2020). This is right for non-irrigated and non-shaded conditions, but in AV systems the incoming solar **radiation** for crops is strongly reduced and consequently, this variable should be integrated into the analysis. Until now, the initial hypothesis usually adopted by researchers in recent AV studies is that the effect of panels on environmental conditions is complex, affecting all the **microclimate** variables (radiation, temperature, humidity, wind, precipitation) and influencing several **physiological processes** of crops in unexpected ways. From an eco-physiological point of view, it is the case. However, from an **agronomical** point of view, requiring an operational and practical perspective, most of the eco-physiological effects have minimal relevance, and their importance lies in their **integrated effect** translated into seasonal variables (the **final resources used** and the **final yield produced** by the system).

The optimization of the interplay between water use and yield in AV systems (with **operational and management purposes**) may be addressed by the use of **parsimonious modeling** (as proposed in this thesis) since it permits simplifying the analysis by focusing on the limiting factors affecting the **agronomical seasonal variables** and by considering the genetic, soil and landscape characteristics and most of the agricultural practices as static **specific parameters** of a specific agricultural scenario (Ritchie and Alagarswamy, 2002). In this work, the analysis of AV systems was oriented into the main **limiting factors** affected by the presence of panels, assumed they are essentially air **temperature**, **radiation** and **water** availability, the latter affected by rainfall and **irrigation**. This choice is justified by the fact that several authors usually link crop yield to these variables (e.g., Monteith, 1965; Özkaynak, 2013; Steduto et al., 2012). Now, the arising question is, which are the most relevant variables affecting the final water use and crop yield in AV systems?

To answer this question, firstly we must discuss the role of air temperature in AV systems, since it is usually linked to yield as the **main** (or the only) **driving factor** for crop growth in



several agronomic research studies (Hatfield and Prueger, 2015; Luo, 2011; Ritchie and Nesmith, 1991) affecting both yield and water use (for example, by controlling leaf development). As shown in Chapter 5 (by experimental data) and as discussed in Chapter 6 (from a modeling perspective), this premise is not completely true for AV systems. This is probably because the effect of panels on **air temperatures** and **radiation** is **decorrelated**, being minimal (around  $\pm 1.5$  °C variations during the day) for air temperature but strong for radiation, as shown in the experiments of Chapter 5. The minimal effects of panels on air temperatures presented here are consistent with similar trends reported by other studies in AV systems (e.g., Barron-Gafford et al., 2019; Marrou et al., 2013). Concerning water use, the variations of air temperature in AV systems have a minimal impact on the **reference evapotranspiration** ( $ET_0$ ) as we can observe in Figure 7.1. The latter is explained by the fact that **radiation** is the first-order factor driving **water consumption** in crops by reducing directly the  $ET_0$  in a roughly **proportional manner** in the Penman-Monteith equation (Irmak et al., 2005; Zotarelli et al., 2010).

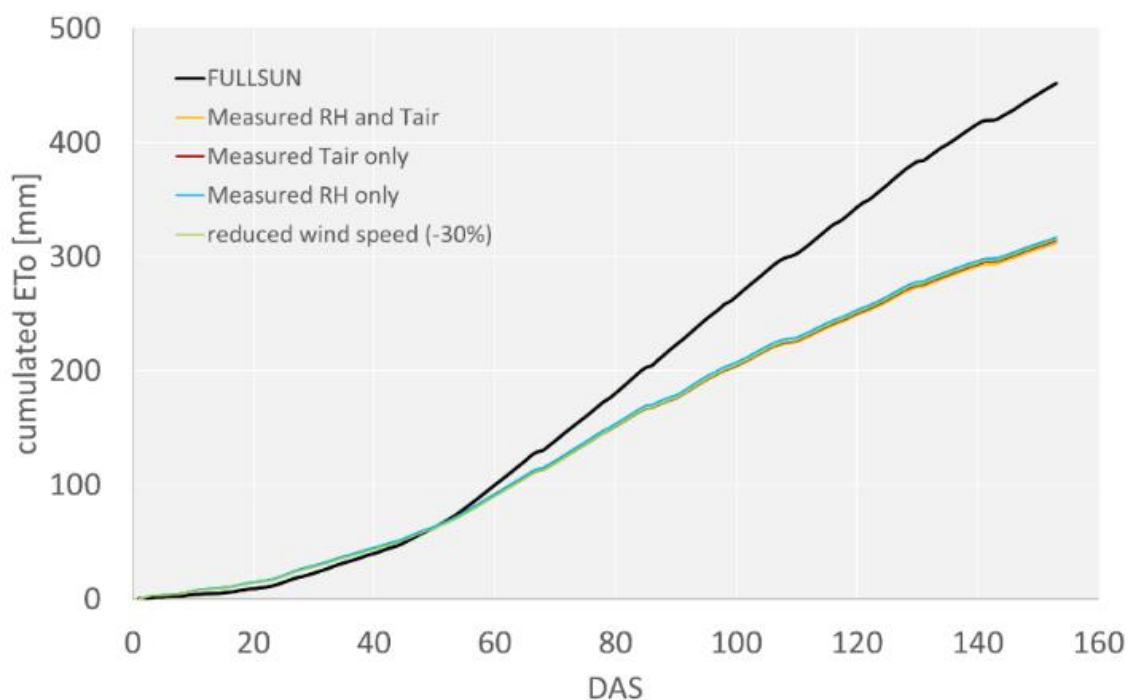


Figure 7.1. Study case: sensitivity analysis of the variables involved in  $ET_0$  estimations (using Penman-Monteith equation), with air temperature ( $T_{air}$ ) and relative humidity (RH) measured under the DAV device during 2019. The FULLSUN curve (black) is the  $ET_0$  computed with data measured in FULLSUN conditions. In the case of wind speed, it was not measured under the DAV device. A hypothetical value of 30% reduced wind speed under the DAV device was used.

This implies a new premise for parsimonious modeling of crops in AV systems, suggesting that we must consider **radiation** and **water availability** as the main first-order variables controlling the interplay between **water use** and crop **yield**. Hence, for operational purposes, we can design optimization scenarios based on simple relationships between the final variables of interest and these both limiting factors (radiation and water), removing the air temperature as a relevant variable for modeling crops in AV systems and giving a **secondary role** to this variable (driving crop development but considering the decorrelation between temperature and radiation).

This is important in future works since, even if the influence of radiation in crop growth is self-evident, this decorrelation is not considered in crop models and most of them use the air temperature as the first-order order variable for crop growth (leading to large errors of simulated yield and water use in AV systems, as shown in Chapter 6). However, it must be considered that in the cases where the presence of panels will reduce temperatures and wind speed to a large degree, these reductions, combined with high humidity, may significantly reduce evaporation and transpiration, regardless of the radiation reduction (Möller and Assouline, 2007; Valle, 2017).

### 7.2.2 Is the net shading rate a proper factor in forcing the optimization of the interplay between water use and yield in AV systems?

In Chapter 6 the use of a factor called “**shading rate**” (which refers to the net reduction of solar radiation over time and space in AV systems compared to a full-sun plot) was shown to be surprisingly powerful to describe the effects of AV systems on crop growth and water use. The success of this simple factor lies in the fact that both variables (yield and water use) can be related to solar radiation, since it has a direct causal effect on both **photosynthesis** and **evapotranspiration** processes, respectively. Several studies confirm these relationships, but the arising question is if can use a simple and averaged shading rate as a **forcing variable** in modeling water use and yield without considering the **variability of radiation** in time and space (for daily modeling). In this sense, one of the most research innovative features of this work was the study of the combined and independent effects of shade and water deficit on maize production for a wide range of **contrasted situations**, going from rained and high-shaded conditions to fully irrigated and full-sun conditions. The main results permit us to observe the role of both limiting factors, suggesting that the **key factor** is **shading** since water availability has a subordinate role (the shading affects evapotranspiration and reduces water needs for irrigation).

The presented work suggests that we can use the simplified shading rate as a key driving factor of yield. As shown in Figure 7.2a, the yield responds to the shading rate in AV systems fitting a non-linear polynomic curve. The response curve in Figure 7.2a is consistent with the statement of Laub et al. (2022) who proposed that the **yield response** to shading rate may be described by **response curves** depending on the crop tolerance. The results presented also suggest that the heterogeneity of the available solar radiation for the crop does not affect the final yield. As shown in Figure 7.2, the yield measured in AVhalf plots (characterized by strong heterogeneity of radiation) is comparable to the yield measured in DAV plots (characterized by more homogeneous radiation).

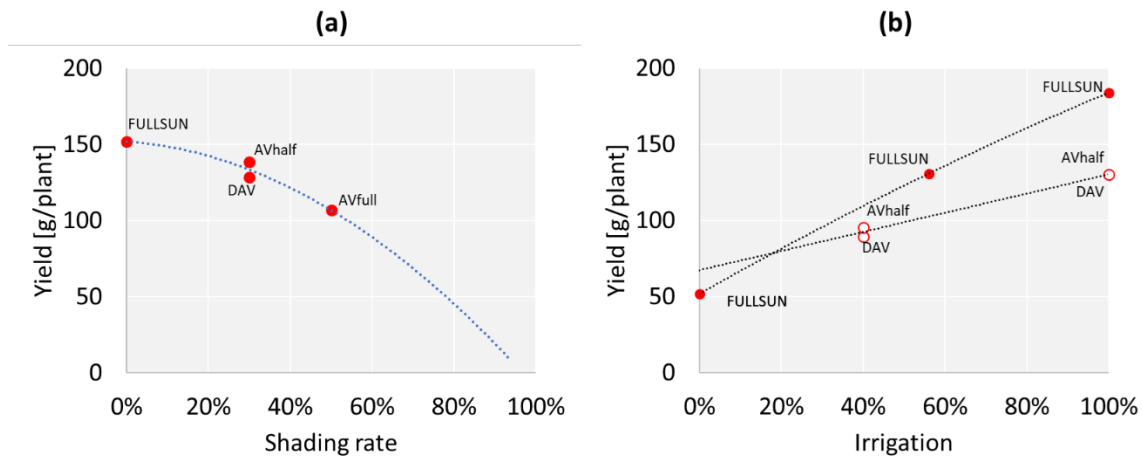


Figure 7.2. (a) The yield response to shading rate under fully irrigated conditions of the three shading rates studied by the experiments in AV systems (FULLSUN = 0%, DAV and AVhalf = 30%, AVfull = 50%) using the 2019 data and (b) the yield response curves to irrigation for the two irrigation conditions (fully-irrigated = red circles and deficit irrigated = white circles). In (a) the shading rate is the ratio between the averaged radiation measured under the AV devices and the amount of radiation in full-sun conditions and in (b) Irrigation is represented by the ratio between the irrigation applied in the plot (shaded or deficit irrigated) and the amount of irrigation in fully-irrigated and full-sun conditions.

Concerning the relationship between shading rate and final water use, in Figure 7.2b it can be observed that the **response of yield to irrigation is proportional** (in shaded and full-sun conditions), following a **linear curve**. This is in line with the well-known generalized relationship of yield to irrigation proposed by several authors (e.g., Stone et al., 2006) in which yield responds linearly to irrigation amount until reaches a **maximal point** in which any increase in irrigation will cause any increase in yield. In Figure 7.2b it is also observed that the slope of the linear response decrease in shaded conditions.

These central findings support the use of shading rate as proposed in Chapter 6 and are of valuable applicability for **crop modeling** in AV systems since one of the main interrogates is if the **heterogeneity conditions** strongly affect the final yield and water use (two main variables of interest for **agronomical decisions**), which seems to be irrelevant at the **plot and seasonal scale**. In consequence, we can suppose that it is possible to use Optirrig (adapted for AV systems as proposed in Chapter 6) for modeling crops under another **dynamic** (but also **fixed**) **AV devices**, based on **shading rate**, and using this factor as a variable for **optimizing scenarios**.

Moreover, we can state that the yield losses will depend essentially on the control of the shading rate, while the management of water availability will have a secondary role in non-limiting and irrigated conditions (in which irrigation practices should be adapted to the reduced needs under shading). However, in water-limited conditions or in rainfed this role may be inverted, with the shading strategies adapted to avoid or reduce water stress. These rules can be helpful to design *in silico* experiments to optimize targeted variables for operational purposes based on **shading levels** and **subordinated irrigation strategies** with parsimonious crop models. However, we must keep in mind that this statement may not be true for other types of crops with different **canopy structures** (Morille et al., 2012). In this sense, the use of other parameters such as **ground cover** and **clump leaf area index** may replace or complement the **leaf area index** in crop models to simulate AV conditions since they are more instructive for **heterogeneous canopies**, according to Asrar et al. (1992).

Finally, we must consider that the effects of shade on yield reduction will vary for the different **field crops**, according to the state of the art in Chapter 3. In this sense, the main limitation of this work is that the only crop studied here was **maize**, considered a **shade-intolerant crop**, in **Mediterranean conditions** (warm to hot with dry summers). In consequence, the results presented here can hardly be extrapolated to other **crops, varieties**, and agro-pedo-climatic **conditions**. However, the fact of selecting the maize crop as a model lets us think that the potential benefit of AV systems is higher for other crops (or maize varieties) more tolerant to shade. For example, **shade-tolerant** varieties of maize (e.g., Bidhari et al., 2021) may help to increase productivity under the same conditions studied here.

Other field crops that have proven some **tolerance** to shade may be envisaged, such are **winter wheat** (*Triticum aestivum L.*) and **barley** (*Hordeum vulgare L.*) (Arenas-Corraliza et al., 2019). Specifically, we can expect better shade tolerance in **C3 field crops** compared to C4 ones (such as maize). This is because C3 crops are **adapted to lower light** conditions, making them more efficient at capturing and utilizing **diffuse light** (Li et al., 2014) and because C3 crops utilize more efficiently **fluctuating light** than C4 crops (Li et al., 2021b). Thus the **reactivation** of **photosynthetic carbon assimilation** during high-radiation after a low-radiation interval is generally faster in C3 than in C4 leaves. Also, **breeding** improvements in **photosynthetic efficiency** of crops (Zhu et al., 2010), are providing new opportunities that may help to reduce the yield reductions in AV systems.

### 7.2.3 Designing shading and irrigation strategies for optimization scenarios by modeling

Putting the **agronomical interest** ahead, optimization scenarios should first focus on limiting yield losses and then on optimizing water use. Now, considering the simplification assumptions from Figure 7.2, the hypothesis is that there may be a **trade-off** between **limiting yield losses** through **modifying the shading rate** and **optimizing water use** (through **modifying the irrigation amounts**). Simple yield optimization can be based on the hypothetical scheme of optimization proposed in Figure 7.3. This scheme suggests that it should be possible to find an optimal case when a certain **shading rate** combined with a certain **irrigation amount** the yield produced will deliver the highest income (or other variable of interest). This targeted variable to optimize will be visualized as a third axis in the plot in Figure 7.3.

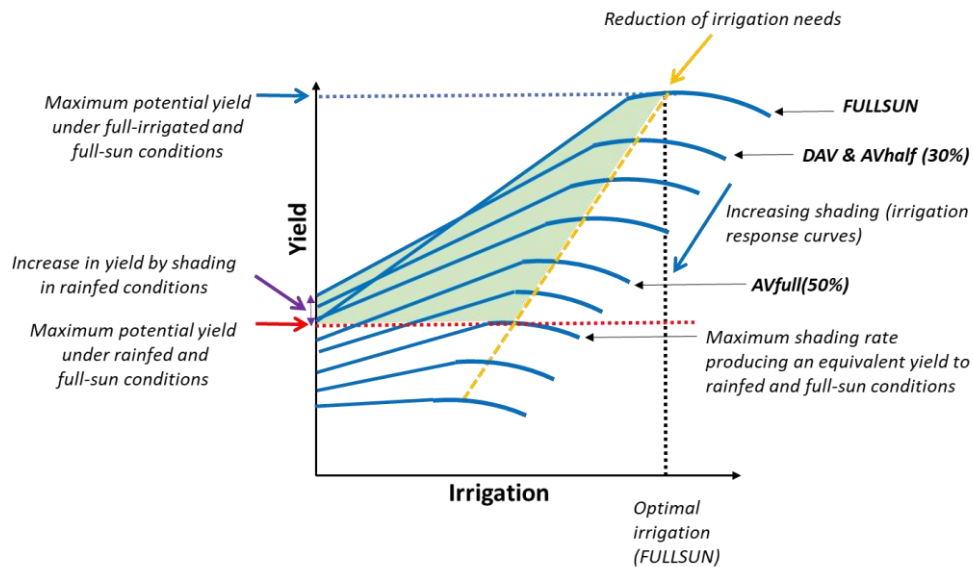


Figure 7.3. Theoretical optimization scheme for crops (based on maize responses). The potential yield will decrease with the shading rate and will increase linearly to irrigation until reaching the maximal yield potential (based on Figure 7.2). The optimization area (in green) is delimited by the yield obtained in rainfed and full-sun conditions, the maximal irrigation amount, and the response curve of yield to irrigation in full-sun conditions. It is supposed that the slope of the irrigation response curves under shading conditions will decrease, as shown by the experiments in Chapter 5). It is expected a small increase in yield under low shading rates, as discussed in Chapter 6 by modeling and as shown by several authors for some field crops as discussed in Chapter 3.

At the **seasonal scale**, the **shading strategies** may be used to fulfill several objectives **during the season**: (i) to limit **water losses** during the whole season and reduce **water needs** during the irrigation period; (ii) to slow **soil drying** during unexpected **irrigation interdictions** in irrigated systems or in case of unexpected **droughts** in rainfed systems; (iii) to protect crops from **heat stress** during a heatwave; and (iv) to limit shading during the **shade-sensitive** periods of the crop (to, e.g. during reproductive stages). In irrigated systems with non-limiting available water, the seasonal management of shade should be focused on reducing the negative effects of shade on crops (thus avoiding the water stress factor), for example permitting high levels of shade only during the water stress-sensitive periods of the crop. The daily shading strategies may also be combined with controlled **deficit irrigation strategies** to **optimize water use** and improve **water productivity of irrigation (WPI)**.

However, for designing shading strategies some facts should be carefully considered (i) in all cases (regardless of the crop) the **response to shade** will depend on the **timing, duration, and intensity** of shading within the **day** and throughout the **season**, which should be carefully

managed in shading strategies to minimize the negative impacts on yield; (ii) the response of crops to shading will vary depending on the **species** (having different **metabolism**), the specific **variety** (having different shade **tolerance**), growth **stage** (having different **sensibility**), **environmental** (hot or temperate), and **hydric** (stress or comfort) conditions; and (iii) the **shading in AV systems** will be present during the **entire season** (even if it is minimized), continuously influencing crop yield and water use.

Considering the **generic crop responses** to shade and water deficit of field crops (based on Figure 3.4 in Chapter 3) a **shading strategy** during the season to **maximize maize yield** can be: shading the crop at the beginning of seedling (to ensure optimal soil moisture for emergence), then permitting soil drying until **emergence**, then shading at the first **vegetative stages** (to avoid water stress during this highly sensitive period), then permitting mild soil drying at the stem-elongation stage until **pre-flowering**, then shading during pre-flowering until **flowering** (to protect maize face to the major effects of water stress in flowering) and then minimizing shade during flowering until **maturity** (to optimize assimilation of carbon in grain filling). This is possible since mild water stress is tolerated by maize from late vegetative development to maturity (Kang et al., 2000; Zou et al., 2021). The **delay** observed in flowering (or those of the other phenological stages) may also be used to prevent or dampen the risk of water stress during the critical period for grain set around flowering (Hall et al., 1971), for example in an attempt to match flowering with rain forecasts, especially given the uncertainties in projected future rainfall and water allocations. This could be relevant in regions where rainfall mostly occurs in the early crop growth stages before the crop faces water stress from the pre-flowering to late grain-filling stages, declining crop production.

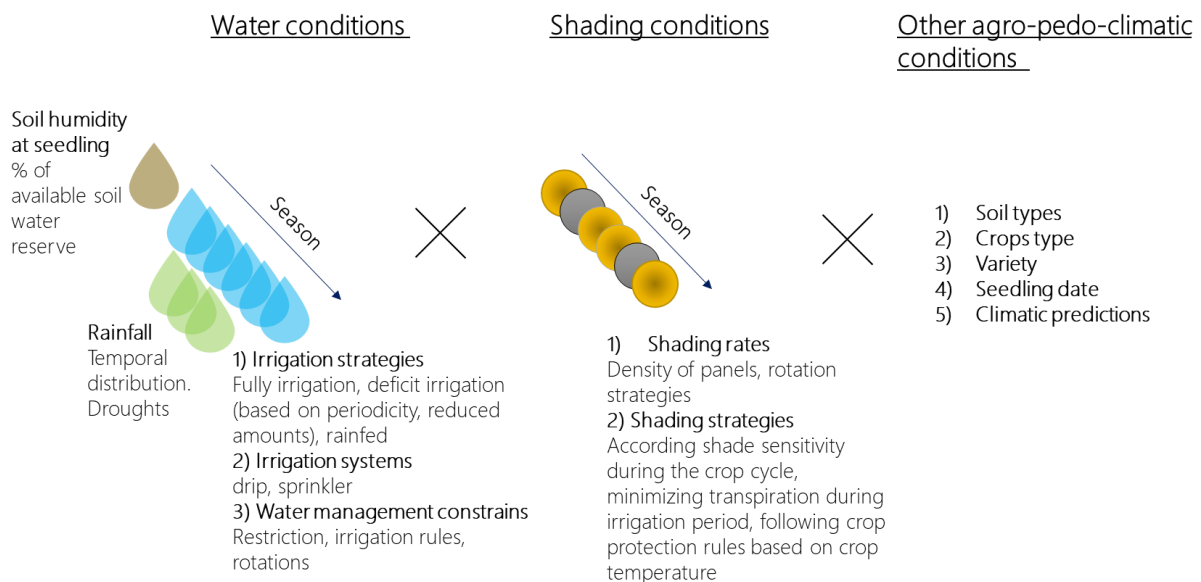


Figure 7.4. A proposed framework to design virtual experiments to optimize irrigation and shading strategies at the season scale.



The seasonal-scale **shading strategies** may be **optimized** by modeling, using **simple models** since they may permit rough capturing of the water and shade stresses at daily time steps, with appropriate **adaptations**. In this thesis, it was demonstrated by the analysis of the **case study** presented in Chapter 6 adapting the Optirrig model to predict maize production considering the effects of shade at a daily time scale. However, a proper evaluation of the model is required. This case study also allows us to think that this adapted version of Optirrig can be used for optimizing **yield and water** concerning **economic** and **financial** variables as proposed by Cheviron et al. (2020). We can imagine that shading and water availability conditions (or different irrigation strategies) imposed during the season can be compared, analyzed and optimized in future **virtual scenarios**. We can include also current and future **climate scenarios** for **different field crops**, to identify the conditions under which AV systems bring added value in an operational context. To achieve these objectives, a virtual experience plan must be designed, executed and analyzed, for example as shown in Figure 7.4.

The **seasonal-scale** shading strategies could also be combined with shading strategies decided at much **shorter temporal** scales (throughout the day) to (i) protect the crop during the **hottest period of the day**, potentially alleviating **water stress** and thereby limiting potential effects on biomass; (ii) to **optimize** diurnal **photosynthesis** until the saturation point is reached, maximizing biomass production; or (iii) to limit to the maximum the **water losses** by evapotranspiration during the day. The combined control of shading at smaller time steps, **allowing shade** in crops during certain periods of the day is expected to be powerful enough to "force" daily and intra-day shading strategies throughout the crop season and the day in predefined or real-time control algorithms for **dynamic AV systems**.

However, the adapted version of **Optirrig** presented here has **limitations** that may be explored in further works. These may imply **additional adaptations** to the model to improve its capacities to address these limitations. For example, these adaptations may permit a more detailed analysis of the system e.g., the consideration of the **spatial heterogeneities** of the system (soil water, soil characteristics, radiation) or the optimization of the irrigation and water productivity at an **intraday time scale**. Hence, the optimization of irrigation and crop production in AV systems can be improved by incorporating crop modeling techniques that account for both **temporal and spatial discretization**, to implement finer strategies of shadow control. Consequently, for finer modeling and optimization scenarios, some important questions arise from this proposed simplified scheme: can we **generalize** the maize **response** to shade to other crops? In which **cases** should be considered the **spatial and temporal variations** of the crop conditions affected by AV systems? These questions will be briefly discussed next.

## 7.3 PERSPECTIVES FOR MORE COMPLEX MODELING OPTIMIZATION

### 7.3.1 Towards modeling discretization for finer simulations?

The irregularity of time and space of the **transmitted radiation to the crop** is an intrinsic characteristic of all AV systems. In this work, the measurements of the **temporal dynamics** realized in two representative positions of AV systems (inter-panel and under-panel positions) have revealed that the **spatial heterogeneity** of the transmitted radiation to the crop is higher in the **fixed devices** compared to the **dynamic** device studied here (controlled by the solar tracking strategy to optimize energy production). This confirms finer and more detailed studies assessing the radiative environment in AV fixed and dynamic systems, suggesting higher heterogeneity of the radiative environment of the crop in fixed devices (e.g., Perna, 2021; Valle, 2017).

From the seasonal experimental results in Chapter 5 (showing equivalent yield in fixed and dynamic AV systems under the same water conditions), and from the case study presented in Chapter 6 (showing the performance of a shading rate factor to account for the global effects of shade on maize yield simulation) we can state that the **spatial heterogeneity** of radiation and the potential **short-term responses to fluctuating light** have **no relevant impact** on the estimation of **final yield** (the main variable of interest). In dynamic devices, this is probably because the cumulated solar radiation in different locations is equivalent despite the dynamic intraday patterns (as shown in Chapter 5), resulting in an equivalent yield from individual plants. This suggests that the **daily-averaged value** can roughly represent the radiative environment for all the plants in these kinds of dynamic devices (using solar tracking control as described in Chapter 5). In **fixed devices**, even if the **daily-averaged** value cannot be representative for all the plants in the plots because of the high variation of the cumulated solar radiation in different locations (as shown in Chapter 5), higher yield of taller plants (in **areas less shaded**) will roughly **compensate** the reduced yield of plants smaller plants (in **areas more shaded**). This will be more valid for AV systems designed or operated to **minimize** the spatial heterogeneity of shading, as shown by Tahir and Butt (2022) in both fixed and dynamic systems.

In terms of modeling, this statement dismissing the need for finer analysis is powerful since it confronts previous conclusions (e.g., Valle et al., 2017) and the general idea indicating that to obtain **accurate crop simulations** from **daily time-step models** (using daily-averaged values), the **radiative environment** of the crop must be measured or modeled with **high spatial and temporal detail**. In practice, that means that numerous sensors and that costly numeric methods and pretreatments (e.g., using 3D or 2D modeling tools) to accurately estimate the radiation reaching the crop are not needed for modeling AV systems in studies requiring only simulations agronomically efficient at a **seasonal scale**. That means also that simple crop models can be employed using daily averaged data (e.g., from the average of inter-panel and under-panel point measurements as shown in this work) to roughly monitor the dynamics and **seasonal indicators of crops** for **management purposes** or to optimize daily shading strategies (e.g., based on daily shading rates).

However, a finer analysis may be required and justified for other situations. Firstly, the homogeneity of the radiative environment can be affected by the **density and configuration of PV panels** in dynamic devices (Amaducci et al., 2018) and can vary according to the **seasonal behavior** of shading under a specific AV system (Weselek et al., 2019), which indicates that the detailed analysis of the radiative environment should be done for each specific AV system,



before to assume that averaged-daily values can be considered as representative of the plot. Also, a **spatial discretization**, which involves breaking down the agricultural plot into smaller spatial units or grid cells, may be necessary, for example in precision agriculture practices or for applications involving spatial management of the plot (considering the radiative heterogeneity and the impacts on soil water dynamics and crop growth).

For example, an interesting application may be the **improvement** of the **irrigation application efficiency** (e.g., varying spatially the volume of water applied by irrigation systems), considering the **super-imposed spatial** and **temporal patterns** or **irrigation** and rain **redistribution**, to compensate for the spatial heterogeneities of soil water content generated by the panels. This will surely require a detailed analysis of the **water budget** fluxes generated by the presence of panels. For this, the methodology proposed in the previous works of Elamri et al. (2018b) may be employed to improve the estimations of **actual evapotranspiration** (which was not addressed in this work but fully explored in the same experimental platform by the authors). The spatial discretization also may permit us to consider in the analysis the spatial variability of **soil properties, topography, management practices**, and other factors that influence crop growth and yield. The incorporation of **spatial data** (soil maps, satellite imagery, gridded meteorological forecast) into crop models may allow it, to improve predictions and open the perspective for analysis at **larger scales** (of several hectares or landscape scale). However, this discretization must also be accompanied and justified by access to **costly material resources** (sensors and data providing the necessary inputs for the model).

On the other hand, the inclusion of **temporal discretization** may be interesting to consider the possible effects of the **short-term crop** responses to **intermittent shading** (Kadowaki et al., 2012; Taylor and Long, 2017) for **intraday management** of shading to accurate estimations of daily water use and biomass produced of crops. This last is important in finer studies because the use of **daily-averaged** values (ignoring the intermittent effects of shade) can lead to significant errors in terms of estimated light interception and carbon assimilation by crops according to Chopard (2021). This will surely need analysis at smaller time steps and other scales (plant and leaf level), in order to adapt shading for an optimal balance between **transpiration** and **carbon assimilation** at a certain moment “t” of the day. This intraday analysis in modeling will surely require the adoption of **mechanistic approaches** to estimate **photosynthesis** and **respiration** processes at a timescale of a few minutes or hours to influence (and improve) prediction at a daily or seasonal scale.

### 7.3.2 The water productivity at leaf scale: A potential indicator integrating water and shade stresses to optimize yield and water use in AV systems?

The potential for optimizing **water usage** in AgriVoltaic (AV) systems is significant, as it can improve the overall efficiency of crop systems. To achieve **finer optimization**, more complex analyses should be conducted at **smaller time scales**, considering the **intraday dynamics** of **radiation**. As mentioned before in Chapter 4, **stomatal conductance** seems to be a **key process** controlled by both **water** and **radiation** conditions, in line with several authors (e.g., Buckley, 2017; Li et al., 2021). Stomata are small pores on leaves that facilitate the **gas exchanges** of **CO<sub>2</sub>** (inflows) and **water vapor** (outflows) between plants and the atmosphere. However, **stomatal behavior** is a **complex process** that requires a comprehensive understanding of several factors and interactions involving plant physiology and genetic mechanisms (Ball, 1988; Buckley, 2017; Jarvis and McNaughton, 1986).

Although the description of stomata behavior is intriguing and it is still an ongoing area of research, **simplifications** should be proposed and implemented for **practical applications**. In a preliminary attempt, a careful analysis of the comparisons in Figure 5.11 leads to a key generalization: the **stomatal behavior** measured for maize leaves under **shade and water stress** seems to be **directly proportional** to **radiation dynamics**. Additionally, we can assume that, in general, stomata tend to **open under shade** to maximize their carbon dioxide uptake (to compensate for the limited energy available) and, on the contrary, they tend to **close under water stress** (to reduce water loss through transpiration, potentially avoiding or mitigating water stress), according to several authors (e.g., Meidner and Mansfield, 1965; Meinzer, 1993).

This generic behavior of stomatal conductance represents a potential tool for **intraday optimization** of water use and yield in AV systems since can be used to describe the integrated **effects of water and shade** deficits on crops (Akita and Moss, 1972; Collatz et al., 1991; Li et al., 2021). Further research in this area could enable **real-time control** based on radiation dynamics (considering shading periods), specifically targeting **water savings** and the reduction of **productivity losses** caused by radiation stress. For example, we can envisage optimization by a simple modeling approach targeting indicators such as **water productivity** at the plant level ( $WP_L$ ), which refers to the amount of photosynthetic carbon gained per unit of water consumed through transpiration. It is calculated using the ratio of **carbon assimilation** ( $A_n$ ) to **stomatal conductance of water** ( $g_{sw}$ ), as shown in Equation 7-1.

Equation 7-1

$$WP_{L(t)} = \frac{A_{n(t)}}{g_{sw(t)}}$$

By **study of WPL** in AV systems we can be used to achieve several **benefits**. Firstly, it allows for the identification of plant **species or varieties** that exhibit **high water use efficiency** and productivity under shade. Secondly, at this level, it should be possible to **optimize WPL** for management purposes by **minimizing transpiration** (saving water) without affecting the **rate of photosynthesis during the day**. This can be based on the **parabolic relationship** between photosynthesis and transpiration, such that transpiration increases as the photosynthesis increases but continues to increase when photosynthesis reached a **maximum** so that ultimately **transpiration efficiency** decreases (as shown under field conditions by Wang and

Liu, 2003). This is particularly important in **water-limited** situations where **maximizing water productivity** during the day becomes crucial (for example during **water shortages** or **heat waves**). Hence, the simulation of daily values of **WPL** can be used to explore and identify **intraday strategies of shading** that minimize water loss while maintaining **acceptable levels of productivity** to complement seasonal strategies. For instance, we can simulate different **diurnal shading strategies** imposing both water and radiation limitations to estimate the rates of biomass production and of water transpiration to evaluate the daily values of water productivity. A **hypothetical scheme** of different **assimilation and transpiration rates** responses to different shading and irrigation strategies is presented in Figure 7.5.

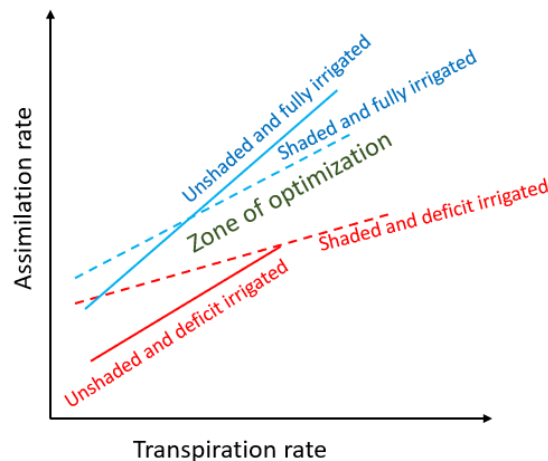


Figure 7.5. Hypothetical scheme of leaf gas exchanges under different shade and irrigation conditions. The zone for irrigation optimization purposes is delimited by the potential behavior of assimilation and transpiration rates under shaded conditions.

The **water productivity at the leaf scale** can also be **integrated at larger scales**, such as the whole plant, ecosystem, or crop level, taking into account factors beyond individual leaves, for example by the approaches presented in Chapter 4 for photosynthesis. However, the simplifications and generalizations mentioned here must be taken carefully. Any **scaling-up of stomatal conductance** to larger scales, such as the **whole plant, crop, or ecosystem** levels, or the analysis of extreme environments may result in important errors (Alam et al., 2021; Jarvis and McNaughton, 1986). Specifically, under **moderate to severe water stress conditions**, plants often exhibit adaptive responses to conserve water, including the **closure of stomata**. In such situations, stomatal conductance may not always be directly **correlated with radiation** availability and stomata can **close in response to water stress** before the shading effect. To accurately analyze stomatal conductance and its **relationship with environmental factors** at larger scales or under **extreme conditions**, it is important to consider **sophisticated models** and **specific measurements** to account for these factors and improve our understanding of the interactions between stomatal conductance, photosynthesis, and environmental condition to optimize these the intraday shading strategies.

# CHAPTER 8

## GENERAL CONCLUSIONS



## CHAPTER 8 – GENERAL CONCLUSIONS

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This thesis presents a cohesive study centered around comprehensive research that involves characterizing the response of a reference field crop (maize) to shaded environment in AgriVoltaic systems under different water conditions. To achieve this a combination of experimental findings and modeling efforts was carried out. It also compares fixed and dynamic AgriVoltaic systems, to compare them and evaluate the potential agronomical benefits of dynamic ones in their capacity to reduce the potential spatial heterogeneities of crop production and soil water content in fixed AgriVoltaic systems. In this work it was also evaluated the effectiveness of the Optirrig model, a parsimonious model, in simulating maize growth and water consumption, with the aim to open the possibility to extent, in further research, the exploration of other scenarios not tested in this thesis.

The main agronomical objective was to analyze how shading from AgriVoltaic systems combined to water regimes impact the development of maize under field experimental conditions. Overall, the experiments conducted in this study demonstrates that, although AgriVoltaic systems can influence microclimatic conditions, their impact on air temperature, humidity, and wind patterns is minimal. In terms of phenology, we can conclude that shade causes delays in plant emergence, which in turn affects subsequent phenological development, including leaf stages and flowering. Additionally, the number of leaves per plant is reduced and the phyllochron (the time required for leaf formation) is longer under shade, also contributing to delayed flowering and leaf area reduction. Water stress exacerbates the effects of shade stress on phenological delay, and may cause flowering failure if it is severe (such as in rainfed conditions). The relationship between leaf emergence and radiation was similar to that with thermal time, suggesting a strong correlation between leaf emergence and radiation received by plants (with potential utility for describing crop growth heterogeneities in AgriVoltaic systems).

Then, a general conclusion is that shading kept throughout the season has significant detrimental effects on maize crop performance, including reduced leaf area, and decreased agricultural production, for the conditions analyzed here. In the case of leaf growth, the effect of shading was proportional to the shading rate (the percentage of radiation reduced in comparison to full-sun conditions) and the combined effect with water stress is cumulative. The effect of water stress was not proportional to the percentage of irrigation reduced in comparison to fully irrigated conditions, this because water stress is more complex process impacting crops and is not a continuous phenomenon (such is shade in AgriVoltaic systems), which suggest that water stress must be better characterized and quantified in further research. The effects of shade and water deficit on leaf growth seem prone to explain the reduced agricultural production (biomass and grain yield). However, the reduction on yield was lower compared to biomass, probably because of photosynthetic internal regulations that must be explored in more into detail.

Concerning water use, it can be concluded that AgriVoltaic systems shown positive effects, reducing irrigation needs and improving water productivity of irrigation in maize crops, while also emphasizing the potential benefits of dynamic structures to reduce soil water heterogeneities. Also, water productivity of irrigation was higher in deficit irrigated plots compared to fully irrigated conditions, opening the possibility to explore combined strategies of water deficit and shade. Also, the preservation of soil moisture in shaded plots can provide

a buffer against water stress and enhance the chances of crop survival in rainfed and dry conditions providing a more favorable environment for crop growth compared to unshaded conditions.

Another initial objective was to determine if the spatial and temporal patterns of shading had any influence on final productivity and water consumption from the soil. The study found that the different shading patterns in fixed or dynamic AgriVoltaic conditions did not have a significant impact on leaf growth dynamics. In terms of water use, the dynamic systems allow to reduce soil water heterogeneities compared to fixed systems. However, in terms of irrigation, our results shown that the same irrigation strategy on both systems resulted in similar yield, suggesting that in fixed systems the heterogeneities on soil water content are compensated by the heterogeneities of individual plants (the production in more vigorous plants compensating the lacking plants). The findings indicate that both fixed and dynamic AgriVoltaic systems can be equally effective in supporting field crop growth and maintaining soil water content. This implies that the decision to choose between fixed and dynamic systems should not necessarily be based on the agronomic impact, which is similar and roughly depends on the net shading rate. Other factors such as panel control needs to optimize the system and increase production homogeneity with specific crops, energy production goals, or financial and societal aspects may play a larger role in determining the preferred system.

Finally, we cannot conclude that the reduction of maize yield losses in shade conditions is systematic, since the shade was applied during all the cycle (without considering crop tolerance nor the phenological sensibility) and thus further research is encouraged to optimize these systems, particularly focusing on shading strategies more adapted to maize. The experimental results encourage further research to explore the interactions between shade, water deficit, and crop responses at different developmental stages and under varying stress conditions and emphasize the limitations of existing crop models in effectively predicting crop yield production.

Concerning modeling, the central objective of this work was to identify key processes affected by shade and to enhance and evaluate the capacity of a simple and parsimonious model to accurately simulate shading effects by simulating maize growth and water budget under (dynamic) AgriVoltaic systems. For this, while focusing on a reference crop such as maize, we used the Optirrig model to adapt it with simple functions based on the conclusions about the responses of maize to shade obtained by experimentation and by integrating the knowledge acquired in generic agronomic models.

From the case study presented here with Optirrig, we can conclude that the over-simplified functions implemented in the model to describe intercepted radiation, leaf growth and photosynthesis are not adequate to account for the effect of shade in AgriVoltaic systems, and require specific adaptations. The main targeted variable to accurately describe the impact of environmental changes on plant development should be radiation interception. An adequate estimation of intercepted radiation, considering the shaded fraction of the plot in AgriVoltaic systems should be the first target for adaptations. The called sun-shade approach and the use of a reduction factor based on the shading rate of the AgriVoltaic systems resulted in good predictions of maize growth, yield and water budget with Optirrig.

From this, we can conclude that a simple separation into sunlit and shaded fractions of the canopy to model intercepted radiation, such in the sun-shade approach, is effective to improve the prediction of biomass production by Optirrig. The proposed simple adaptation using the shading rate to affect key parameters also shown effectiveness in improving simulations with Optirrig, but lack of ecophysiological meaning and its applicability in different contexts or with different shading rates and panel configurations remains uncertain. In terms of water budget, the model Optirrig seems to be robust to predict water soil dynamics on shaded and water stress conditions, which means that only a correct estimation of the reference evapotranspiration reduced by shade is necessary to correct water budget simulations.

In overall, the current structure of the Optirrig model, with the proposed and effective modifications, has demonstrated its ability to correctly simulate the growth of maize in AgriVoltaic conditions under light or moderate water stress. This model can be used for operational purposes to daily monitor or manage the crop, or can be used to simulate other *in silico scenarii* to explore shading and irrigation strategies for agronomic, environmental or financial optimization purposes. However, it is important to keep in mind that the Optirrig model should be used with caution, as it remains a simplified model and requires further validation under more diverse experimental conditions.

However, the model is still inadequate for analyzing the intraday dynamics of biomass production and soil water content, particularly with the perspective of optimizing shading strategies at intraday time scale. For this, a more mechanistic approach may be needed to replace the existing equations in the model or even the inclusion of sub-modules running at a lower time scale (e.g. 1h, 10 min). These improvements should focus on key affected processes (light interception, photosynthesis and transpiration) and the integration of key dynamic processes such as stomatal conductance or photosynthesis-transpiration coupled models. Incorporating temporal and spatial discretization into crop modeling scenarios holds promise for accurate maize yield prediction in heterogeneous conditions. By considering dynamic processes throughout the growing season and accounting for spatial variability within agricultural landscapes, more detailed and precise predictions can inform better decision-making for crop management and yield optimization. Finally, intermittent shading combined with irrigation scheduling strategies should be considered for integrated water management in AV systems, aiming for improved water use efficiency and crop productivity.

The overarching objective of this thesis was to gain insights into the agronomic implications of AgriVoltaic systems and their potential for enhancing crop productivity and water management for field crops, taking the maize crop as reference by employing experimental and modeling efforts. By thoroughly examining the effects of different shade conditions provided by various AgriVoltaic systems, as well as different levels of water stress, the research contributes to a deeper understanding of the interplay between shade, water availability, and maize growth. The findings of this study hold significant promise for informing optimized strategies for irrigation and shade management in AgriVoltaic systems, ultimately leading to improved crop yields and more efficient water utilization.





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